(High field) Transport properties of strongly correlated metals

Cyril PROUST

Laboratoire National des Champs Magnétiques Intenses

Toulouse, France

http://www.lncmi.cnrs.fr **http://www.emfl.eu**

Outline

1. Definitions & Reminders

2. Experimental techniques

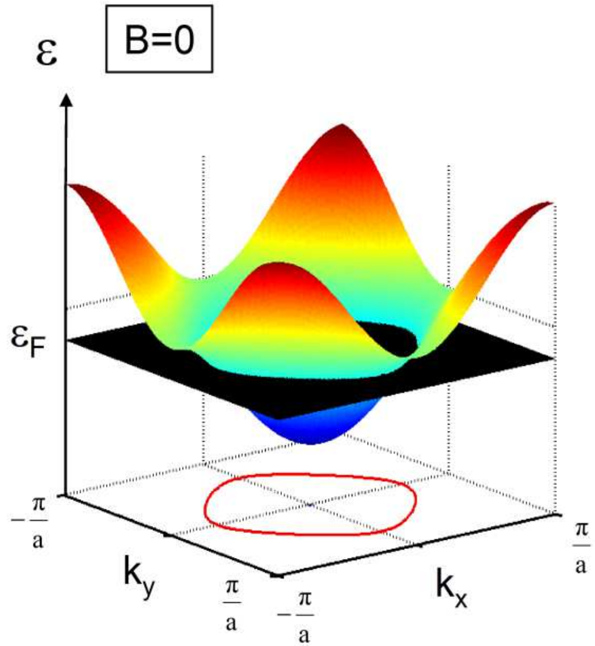
3. Transport properties of SCES

4. High field transport measurements

1. Definitions & Reminders

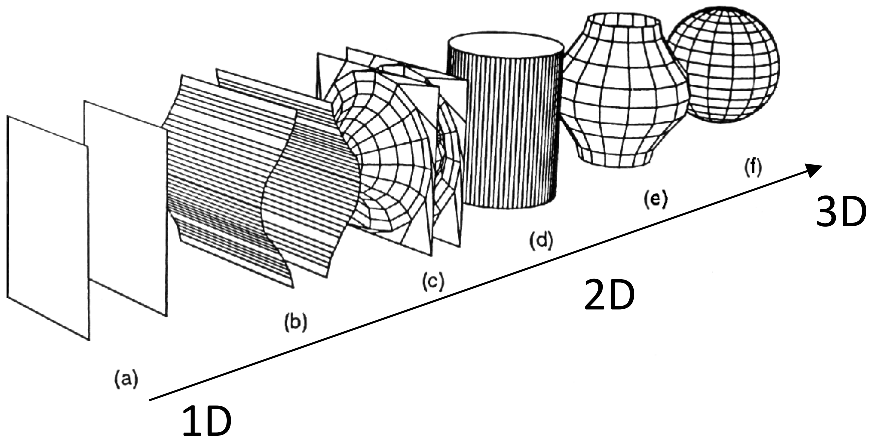
Reminders

Band theory at2D: $\varepsilon(\vec{k}) = -2t\left(\cos(k_x a) + \cos(k_y b)\right)$



ε_F ~ 1-10 eV

Typical excitations (ΔV, ΔT) ~meV



Comparison with band structure calculations, effect of interactions, phase transitions…

FS measurements → Global properties: C_v, χ_{Pauli}, R_H, $\Delta\rho/\rho$...

FS measurements → Topographic properties: ARPES, AMRO, QO

Reminders

Global properties

- **Specific heat**

$$\boxed{C_v = \frac{\partial U}{\partial T} = \frac{\pi^2}{3} k_B g(\varepsilon_F) \times T}$$

where $U = \int_0^{E_F} \varepsilon\, n(\varepsilon) f(\varepsilon) d\varepsilon$

$$g(\varepsilon_F) = \frac{m^* k_F}{\hbar^2 \pi^2}$$

- **Hall effect**

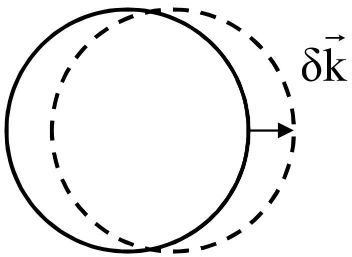
$$\boxed{R_H = \frac{\rho_{xy}}{B} = \frac{1}{nq}}$$

- **Magnetoresistance**

$$\vec{J} = ne\vec{v} = e\int_{SF} \vec{v}\, \frac{\delta\vec{k}.d\vec{S}}{4\pi^2}$$

where $\delta\vec{k} = \frac{e\tau}{\hbar}\vec{E}$

$$\boxed{\vec{J} = \frac{e^2\tau}{4\pi^3\hbar} \int_{SF} \vec{v}.d\vec{S}\ \ \vec{E}}$$



Reminders

Drude theory

Electrical conductivity $$\sigma = \frac{ne^2\tau}{m^*}$$ $[\Omega\ \mathrm{cm}]^{-1}$

Thermal conductivity $$\kappa = \frac{1}{3}v_F^2\tau C_v = \frac{1}{3}\ell v_F C_v$$ [W / K cm]

Wiedemann-Franz law: $$\frac{\kappa}{\sigma} = \frac{\frac{1}{3}m^* v_F^2 C_v}{ne^2}$$

if $C_v = \frac{3}{2}nk_B$ and $\frac{1}{2}m^* v_F^2 = \frac{3}{2}nk_B$ $$\boxed{\frac{\kappa}{\sigma} = \frac{3}{2}\left(\frac{k_B}{e}\right)^2 T}$$

$$\lim_{T\to 0}\frac{\kappa}{T\sigma} = L_0$$ where $$L_0 = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2$$

Universal law, i.e. robust signature of Fermi liquid theory, stating that the electronic carriers of heat are fermionic excitations of charge *e*.

Reminders

Boltzmann theory

$f_k(r)$ Distribution function which measure the number of carrier (k, r)

The distribution function can change through

(i) *Diffusion* Carriers of velocity v_k enter whilst others leave

$$\dot{f}_k\Big|_{diff} = -\boldsymbol{v_k}.\frac{\partial f_k}{\partial \boldsymbol{r}}$$

(ii) *External fields* $\dot{\boldsymbol{k}} = -\frac{e}{\hbar}(\boldsymbol{E} + \boldsymbol{v_k} \wedge \boldsymbol{H})$ $f_k \rightarrow f_{k+t\dot{k}}$

$$\dot{f}_k\Big|_{field} = -\frac{e}{\hbar}(\boldsymbol{E} + \boldsymbol{v_k} \wedge \boldsymbol{H}).\frac{\partial f_k}{\partial \boldsymbol{k}}$$

(iii) *Scattering* Several processes throw carries from one state to another through interaction or collision

$$\dot{f}_k\Big|_{scatt}$$

Reminders

Total rate of change: $\dot{f}_k = \dot{f}_k\Big|_{diff} + \dot{f}_k\Big|_{field} + \dot{f}_k\Big|_{scatt}$

$$\boxed{-\boldsymbol{v_k}.\frac{\partial f_k}{\partial \boldsymbol{r}} - \frac{e}{\hbar}(\boldsymbol{E} + \boldsymbol{v_k} \wedge \boldsymbol{H}).\frac{\partial f_k}{\partial \boldsymbol{k}} = \dot{f}_k\Big|_{scatt}}$$ and $$\boldsymbol{J} = \int e\boldsymbol{v_k} f_k dk$$

Boltzmann equation

Rq: (i) Isotropic condition: $$\boldsymbol{J} = \frac{e^2\tau}{4\pi^3\hbar}\int \boldsymbol{v_k} d\boldsymbol{S}\,.\,\boldsymbol{E}$$

(ii) Shockley-Chambers tube integral

$$\sigma_{x\beta} = -\frac{e^3 B}{2\pi^2\hbar^2}\int_0^T \left(\int_0^\infty v_x(t)e^{-t'/\tau(t)}v_\beta(t+t')dt'\right)\mathrm{d}t$$

Quantum oscillations

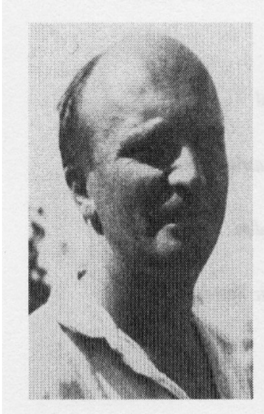
1930 de Haas-van Alphen / Shubnikov-de Haas effect

W.J. de Haas

(1878-1960)

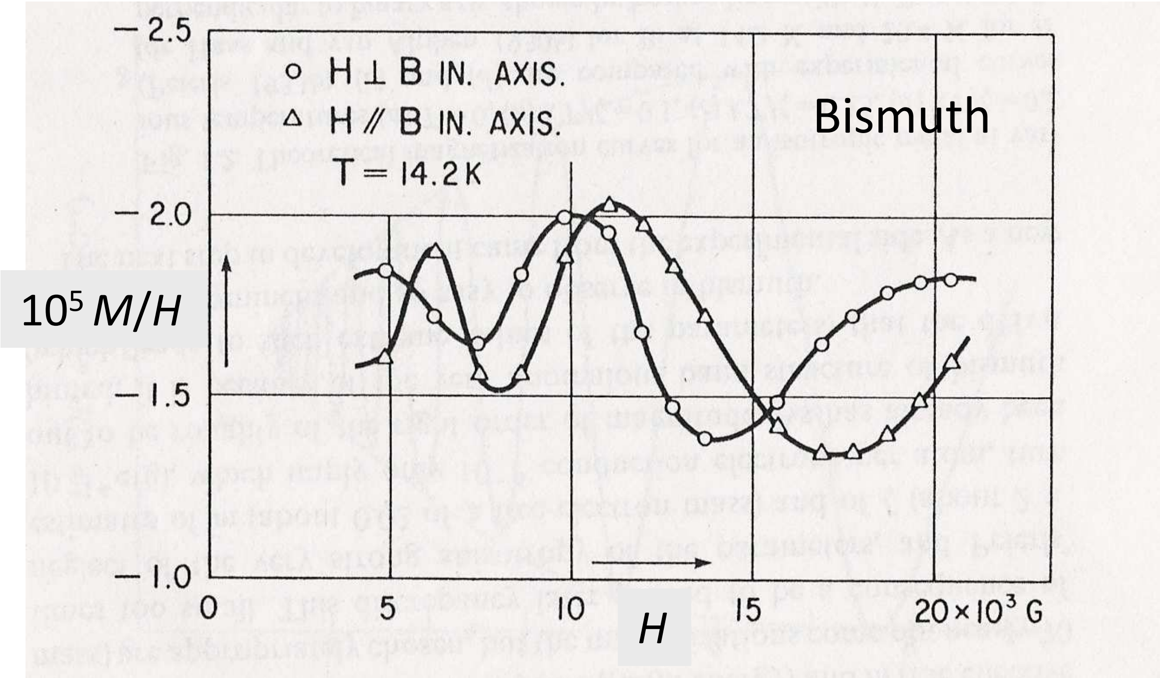
P.M. van Alphen

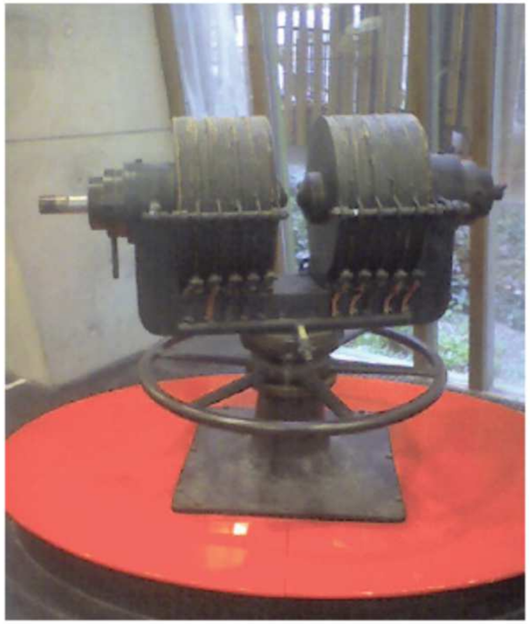
(1906-1967)



L.V. Shubnikov

(1901-1945)



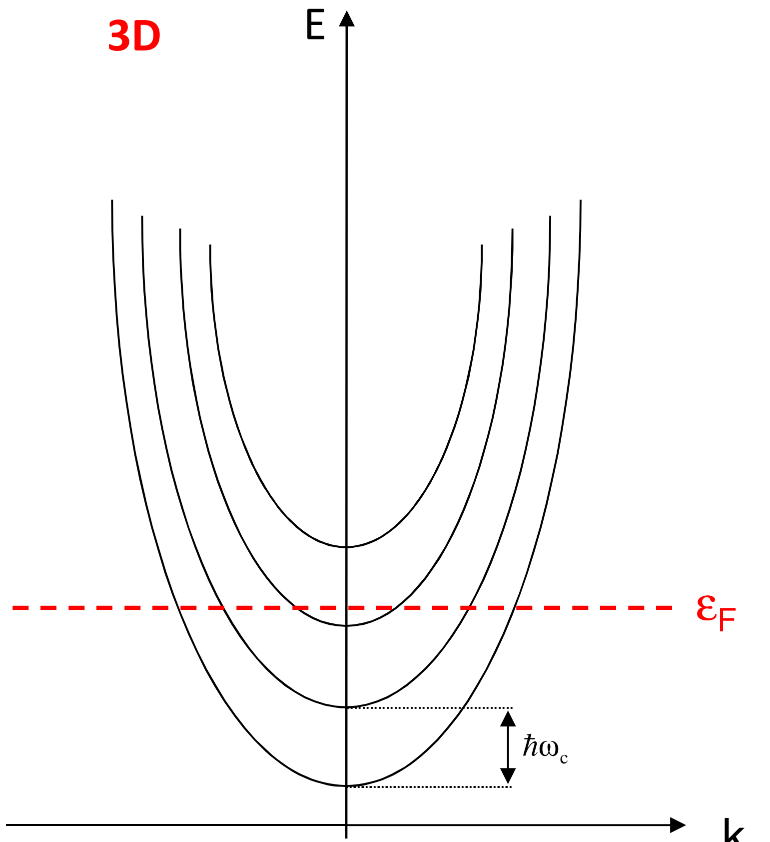


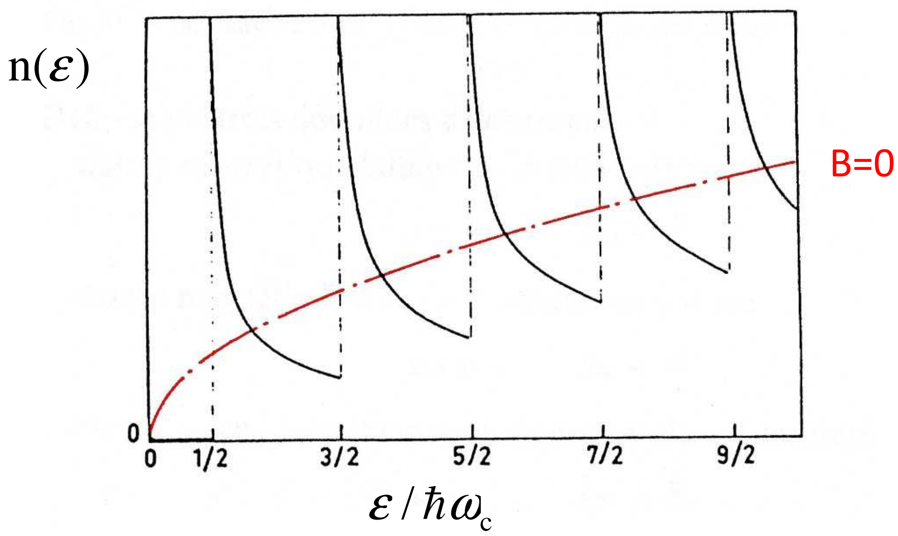
Quantum oscillations

$$E = E_z + E_\perp = \frac{\hbar^2 k_z^2}{2m} + \hbar\omega_c\left(n + \frac{1}{2}\right) \qquad \omega_c = \frac{qB}{m_c}$$

$$n(E) = 2\pi V\left(\frac{2m}{\hbar^2}\right)^{3/2} \hbar\omega_c \sum_{n=0}^{\infty} \frac{1}{\sqrt{E - \hbar\omega_c(n+0.5)}}$$

Density of states





$\Downarrow$

Oscillation of most electronic properties

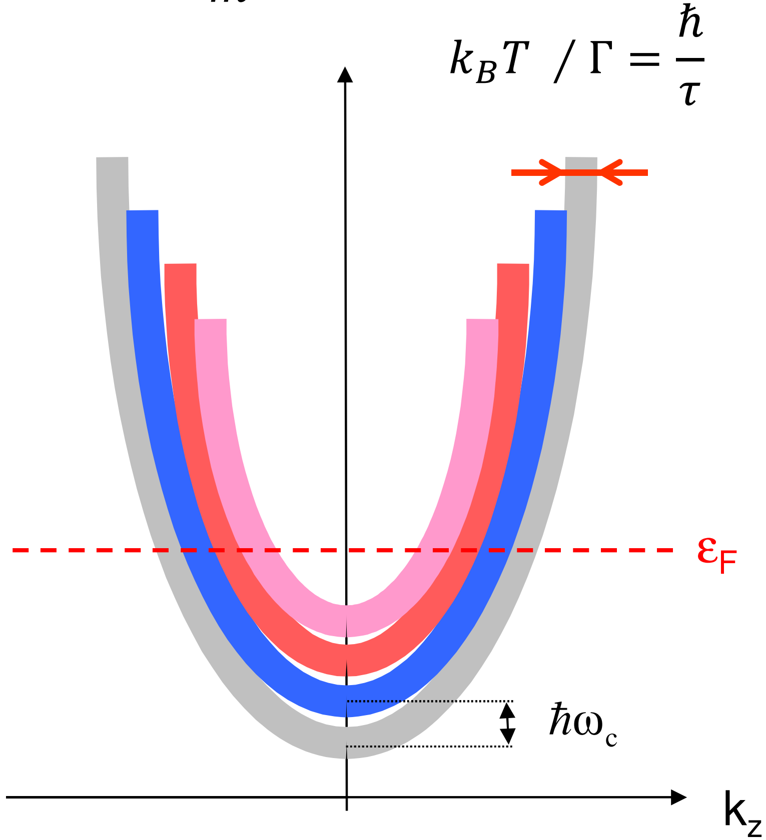
Magnetization: de Haas-van Alphen (dHvA)

Resistivity: Shubnikov-de Haas (SdH)

Quantum oscillations

Temperature / Disorder effects on quantum oscillations

$$\omega_c = \frac{eH}{m^*}$$



- **Low T measurements**

$$\hbar\omega_c > k_B T$$

- **Need high quality single crystals**

$$\hbar\omega_c > \frac{\hbar}{\tau} \quad \Rightarrow \quad \omega_c \tau > 1$$

Quantum oscillations

Lifshitz-Kosevich theory (1956)

T≠0

p=1

$$\Delta R, \Delta M \propto R_T \, R_D \, R_S \sin\left[2\pi\left(\frac{F}{B} - \gamma\right)\right]$$

$\frac{F}{B} = \frac{\hbar}{2\pi q}\frac{A_F}{B}$ Onsager relation $\Rightarrow$ A_F Extremal area

$R_T = \frac{X}{sh(X)}$ where $X = 14.694 \times T m_c / B$ $\Rightarrow$ m^* Cyclotron mass

$R_D = \exp\left(-\frac{14.694 \times T_D m_c}{B}\right) = \exp\left(-\frac{\pi}{\mu B}\right)$ $\Rightarrow$ $T_D = \frac{\hbar}{2\pi k_B \tau}$ Dingle temperature (mean free path)

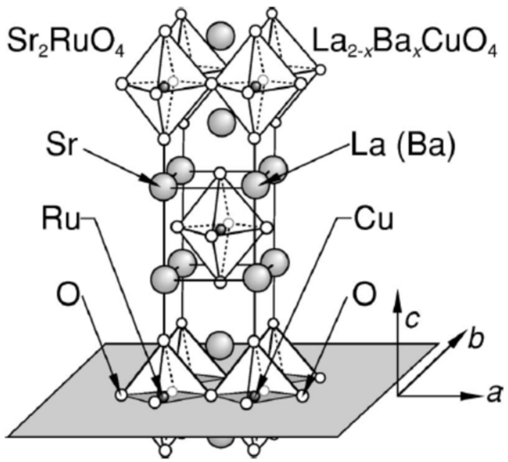
$R_S = \cos\left(\frac{\pi}{2} m_b^* g\right)$ $\Rightarrow$ $m_b^* g$

Direct measure of the Fermi surface extremal area

(but number of orbits ? location in k-space ?)

Rq: Luttinger theorem at 2D $n_{2D} = \frac{2A_k}{(2\pi)^2} = \frac{F}{\phi_0}$

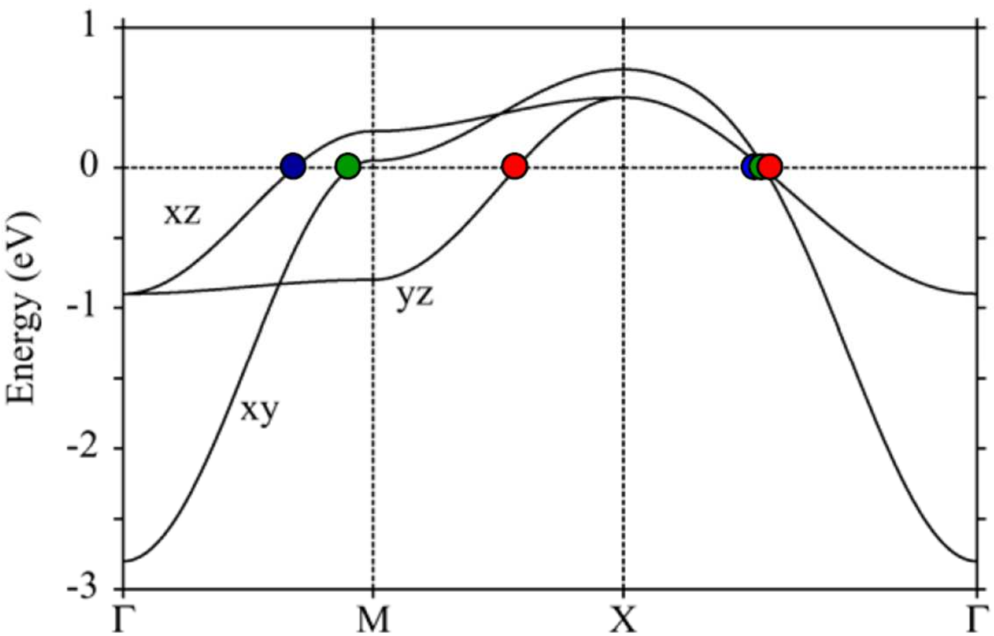
Quantum oscillations: the case of Sr_2Ru0_4



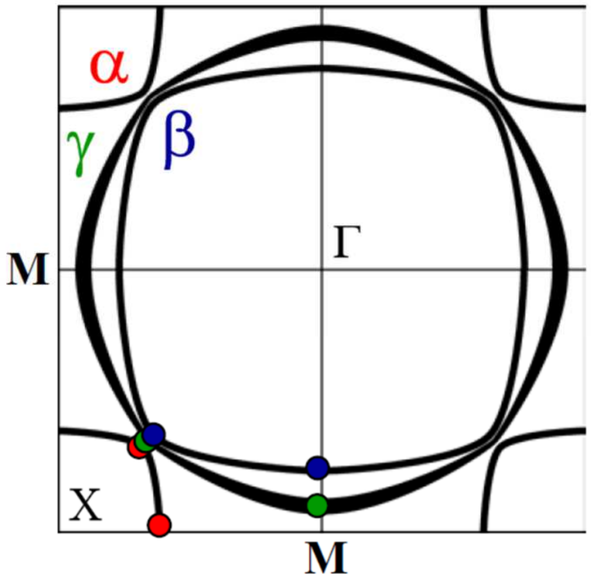
Sr_2RuO_4: a Quasi-2D Fermi liquid

Band structure calculations

3 sheets of FS: α hole like; β, γ electron like

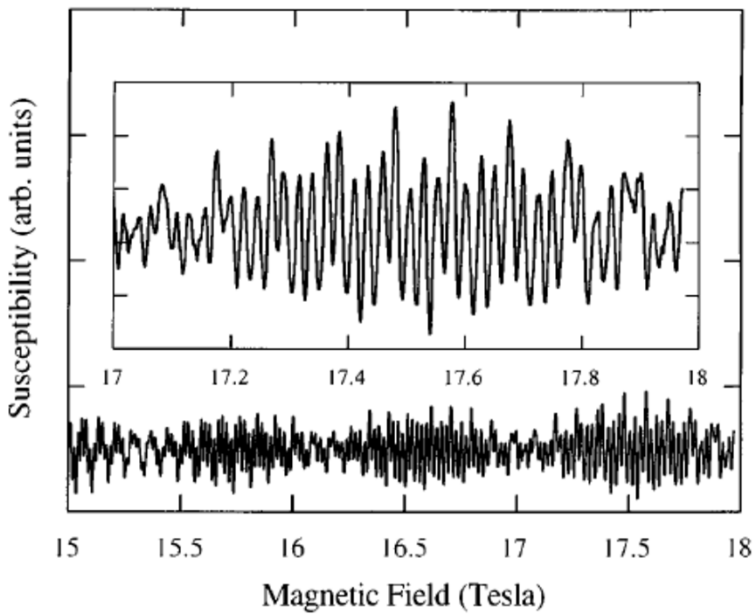


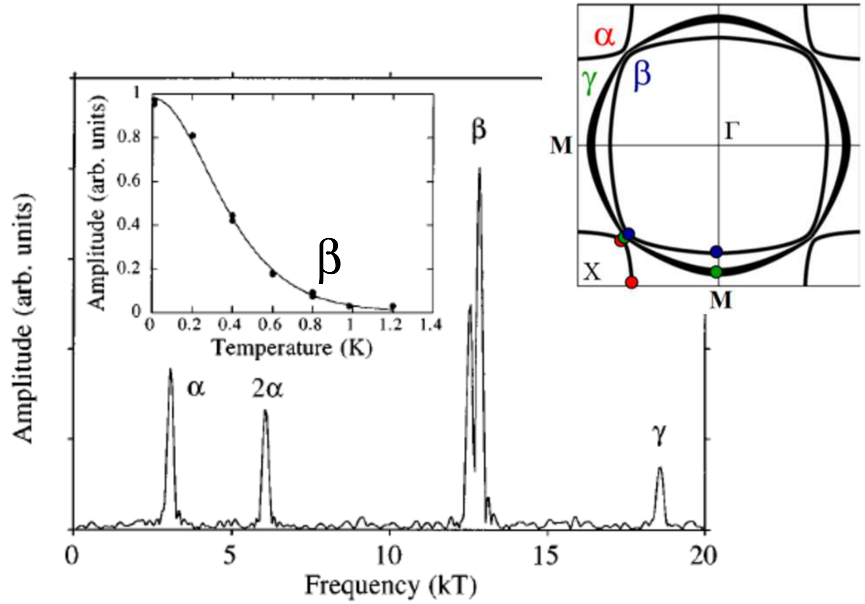
A. Liebsch *et al*, PRL **84**, 1591 (2000)



I.I. Mazin *et al*, PRL **79**, 733 (1997)

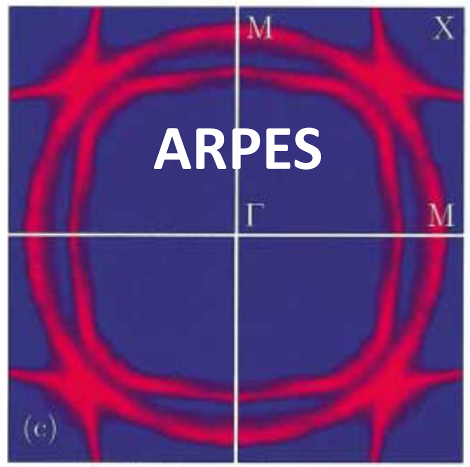
Quantum oscillations: the case of Sr_2Ru0_4





Mackenzie *et al*, *PRL* **76** 3786 (1996)

	α	β	γ
Frequency F (kT)	3.05	12.7	18.5
Average k_F (Å^{-1})	0.302	0.621	0.750
$\Delta k_F/k_F$ (%)	0.21	1.3	<0.9
Cyclotron mass (m_e)	3.4	6.6	12.0
Band calc. F (kT)	3.4	13.4	17.6
Band calc. $\Delta k_F/k_F$ (%)	1.3	1.1	0.34
Band mass (m_e)	1.1	2.0	2.9

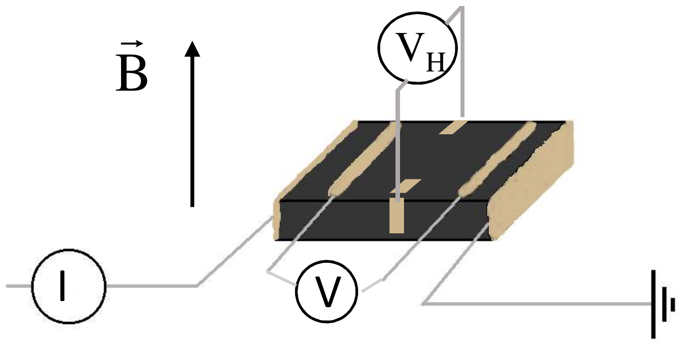


Sr_2RuO_4 cleaved at 180 K
T= 10 K hν=28 eV

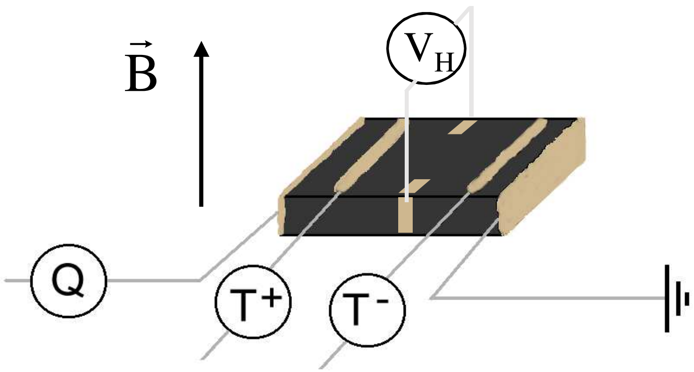
Damascelli *et al*, *PRL* **85** 5194 (2000)

2. Experimental techniques

Electrical transport vs Thermal transport



- Resistivity
- Hall effect

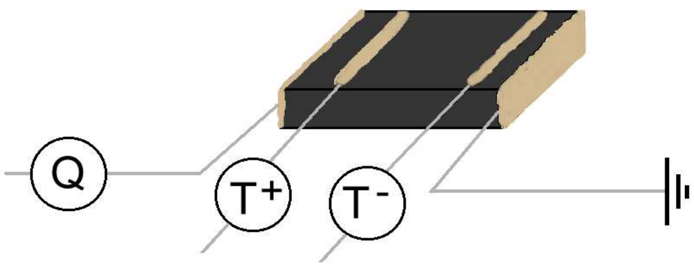


- Seebeck coefficient

$$S = \frac{\alpha}{\sigma T} = \frac{E_x}{\nabla_x T}$$

- Nernst coefficient

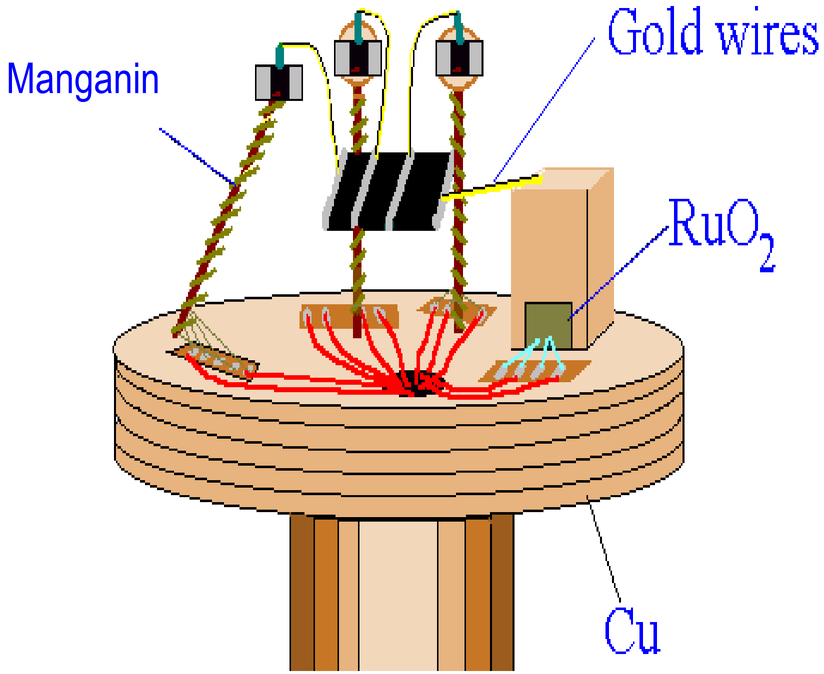
$$\upsilon = \frac{N}{B} = \frac{1}{B_z} \frac{E_y}{\nabla_x T}$$



- Thermal conductivity

$$\kappa(T) = \frac{Q}{\Delta T}$$

Thermal transport setup

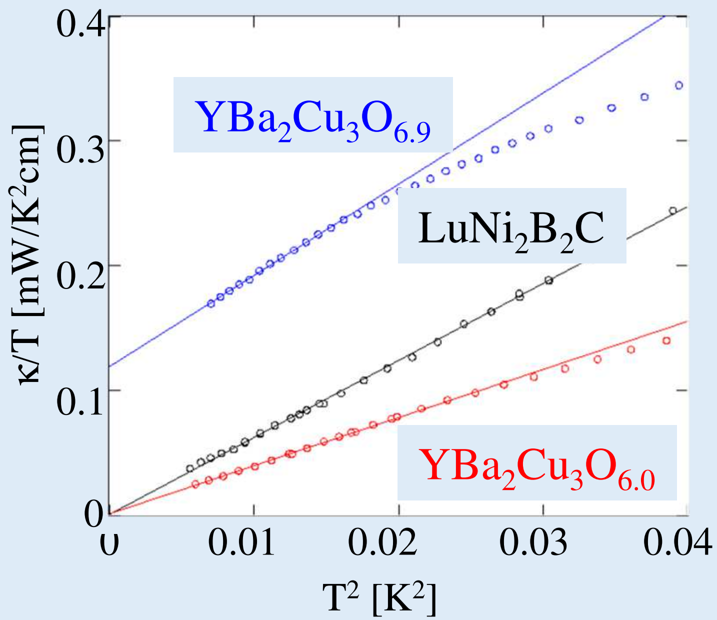


Courtesy of K .Behnia

Subkelvin temperature measurement:

$$\kappa(T) = \kappa_{phonon}(T) + \kappa_{electronic}(T)$$

T^3 $\quad$ T



insulator: a = 0

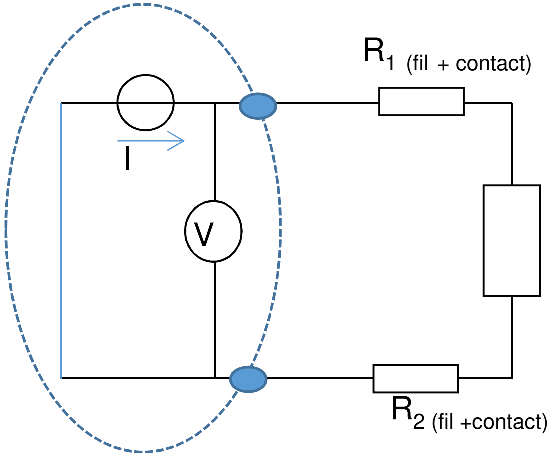
s-wave superconductor: a = 0

d-wave superconductor : a ≠ 0

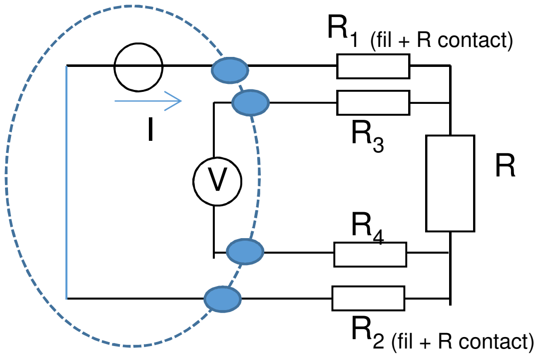
YBCO (optimal)

Electrical transport measurements

2 points measurements

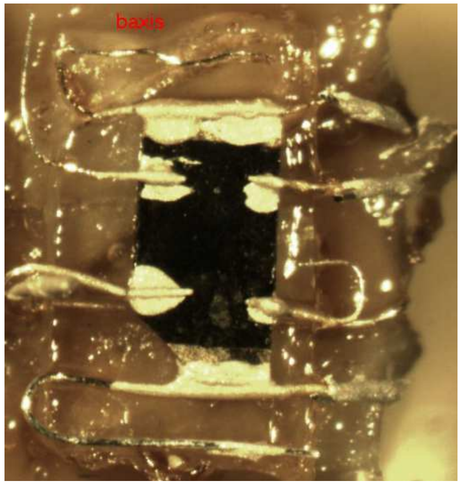


4 points measurements



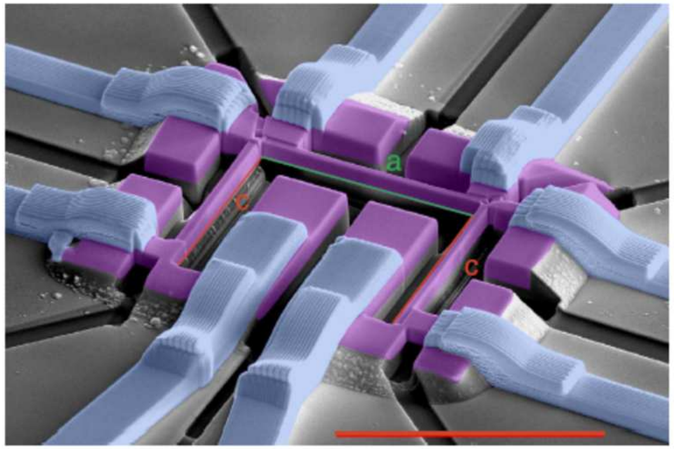
Sample connected with silver paint

~ 400 µm



Microstructures (FIB carved) of $CeRhIn_5$

~60 x 60 µm

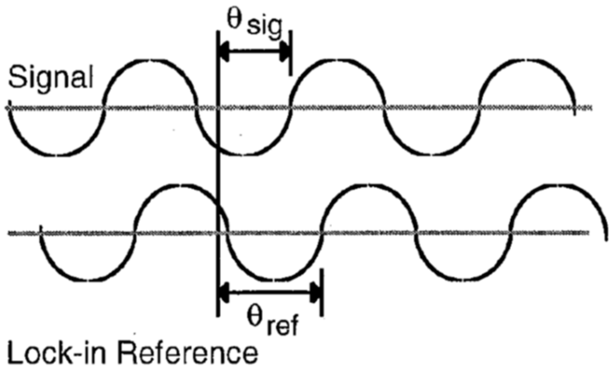


Moll *et al*, *Nature Comm.* **6**, 6663 (2015)

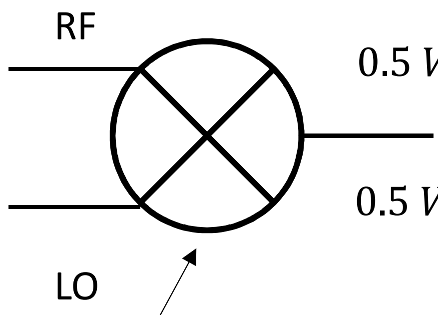
Lock-in amplifier

Phase-sensitive detection

$V_{sig} = V_{sig}\sin(\omega_r t + \Theta_{sig})$



$V_{ref} = V_L\sin(\omega_L t + \Theta_{ref})$

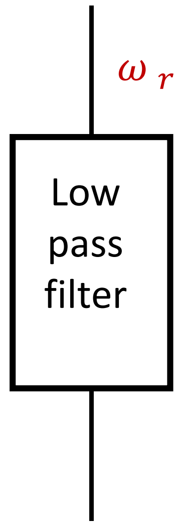


$0.5\, V_{sig}V_{ref}\cos([\omega_r - \omega_L]t + \Theta_{sig} - \Theta_{ref})$

-

$0.5\, V_{sig}V_{ref}\cos([\omega_r + \omega_L]t + \Theta_{sig} + \Theta_{ref})$

$\omega_r = \omega_L$



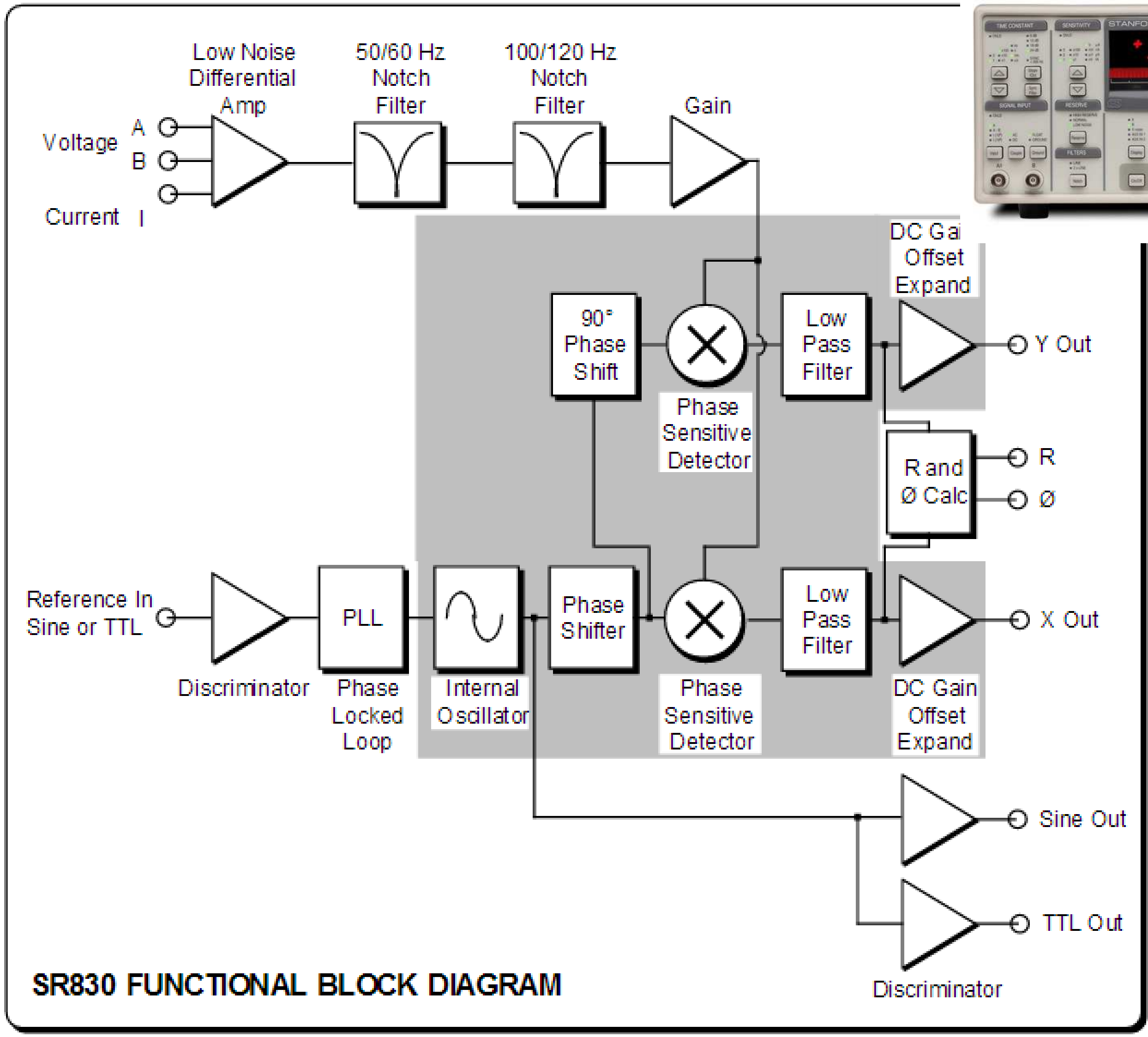
$0.5\, V_{sig}V_{ref}\cos(\Theta_{sig} - \Theta_{ref})$

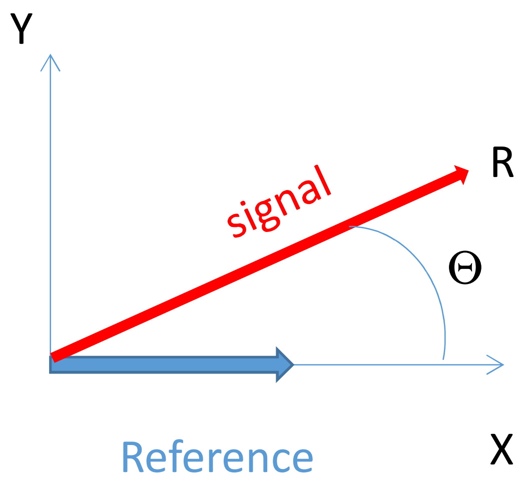
DC signal if $\Theta_{sig} - \Theta_{ref} = c^{te}$

Output of a mixer (PSD) = product of two sine waves

This technique allows to detect the response from the experiment at the reference frequency (narrow band detection much better than a simple filter)

Lock-in amplifier

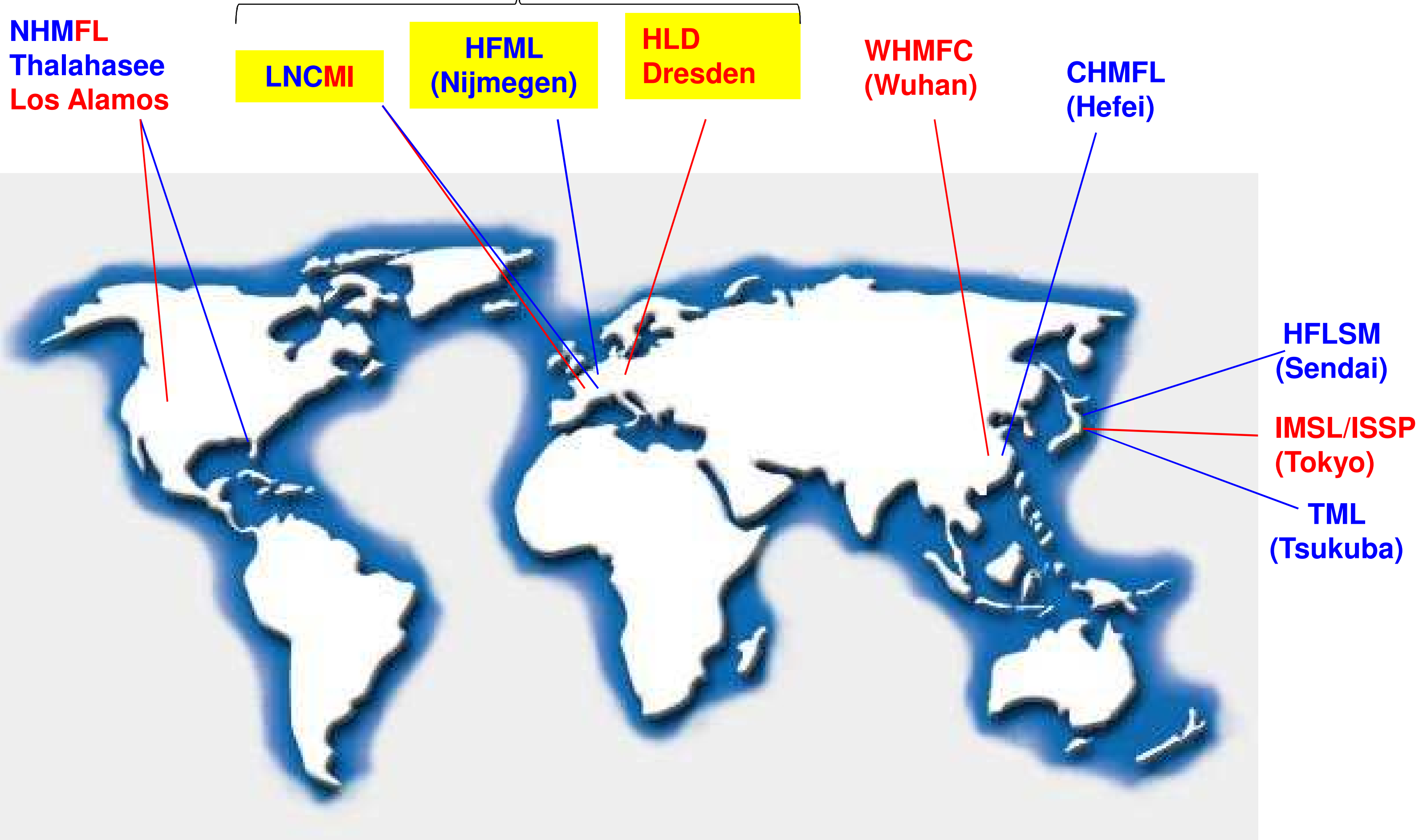




High magnetic field facility

Large high magnetic field facilities (pulsed and DC)

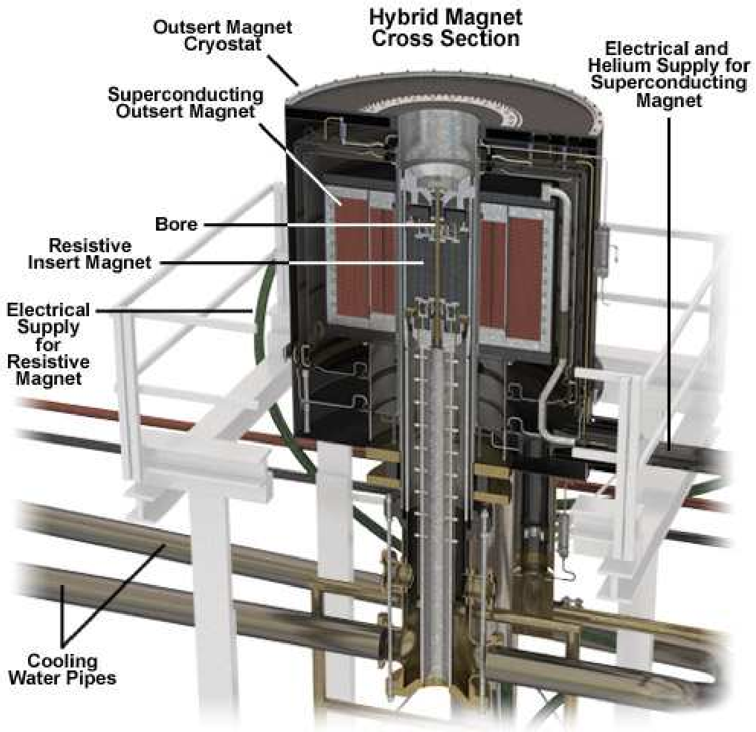
EMFL
European Magnetic Field Laboratory



LNCMI-Grenoble: static fields

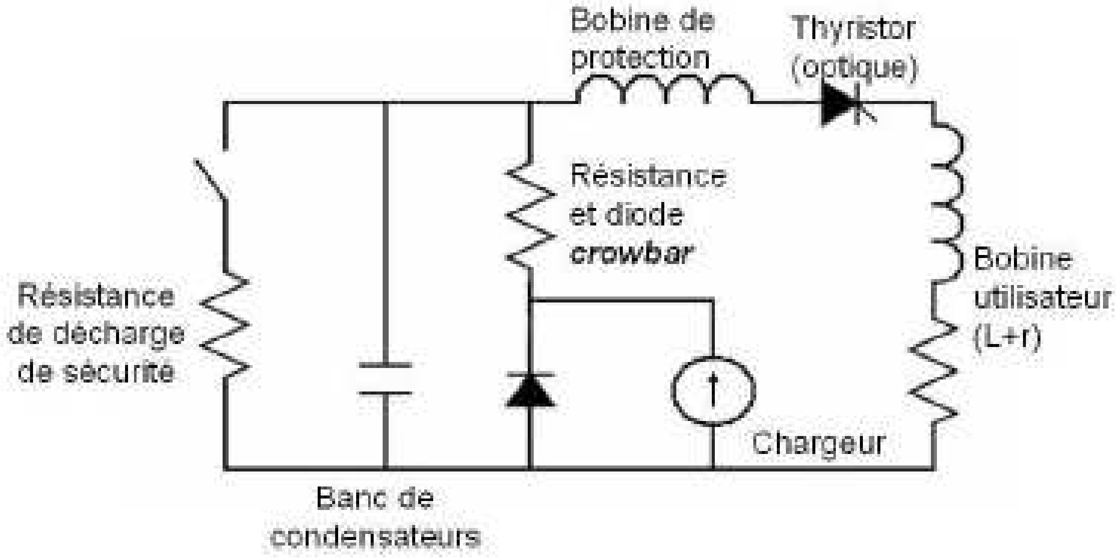
Resistive coil
I_{max} = 32 000 A, P = 24 MW
Water flow ~ 300 L/s (for cooling)
Max. field = 36.5 T

Hybrid project (2019)
34 T (R) + 9 T (SC) = 43 T



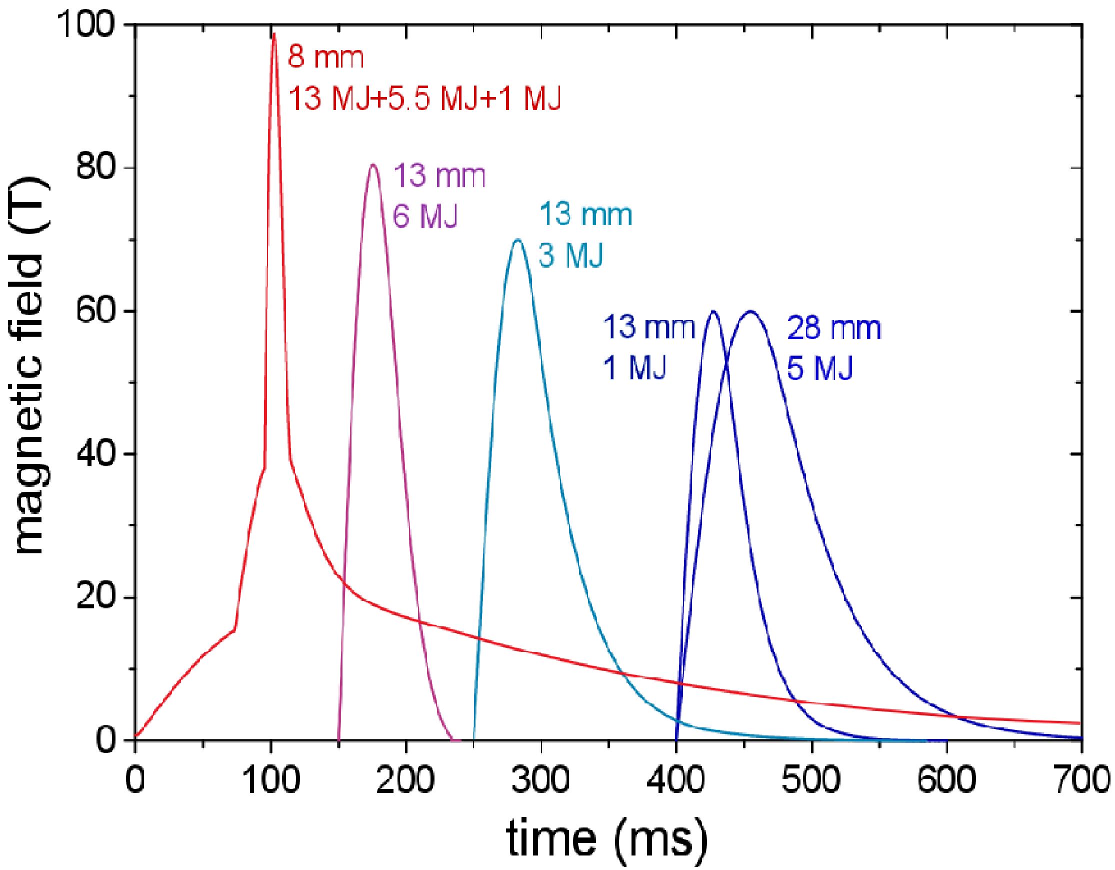
NHMFL Tallahassee (45 T)

LNCMI-Toulouse: pulsed fields

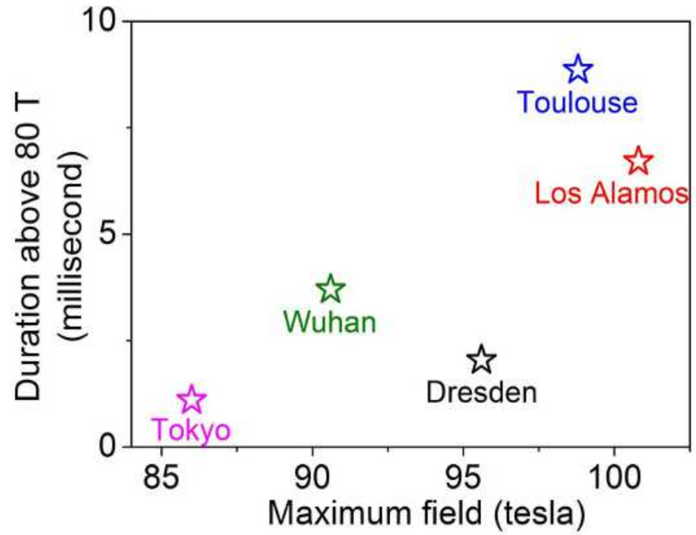


LNCMI-Toulouse: pulsed fields

High magnetic fields up 98.8 T



100 T coil



3. Transport properties of SCES

Inspired by a talk of N. Hussey

Transport properties of SCES

What makes DC transport measurements such an important probe of SCES ?

✓ " Often the first thing to be measured, but the last to be understood…"

✓ " What scatters may also pair "
Hence electrical resistivity is a powerful, albeit coarse, probe of superconductivity

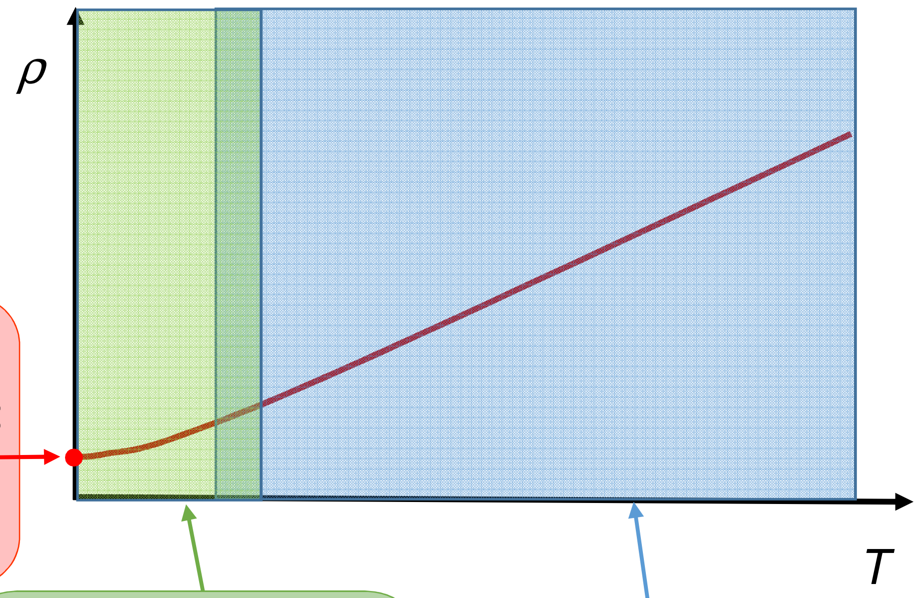
✓ In the Fermi liquid picture the resistivity is T^2 with $A / \gamma^2 \approx 10^{-5}$ $\mu\Omega$ cm mol^2 K^2/J^2

✓ Close to a quantum critical point the resistivity is linear in T

High temperature: bad metals

What constitutes metallic behaviour?

Basic definition: A material whose resistivity increases with temperature



$$\rho(T) = \frac{m^*}{ne^2}\Gamma(T)$$

Scattering rate

T → 0

electron – defect

$$\rho_0 = \frac{m^*}{ne^2}\Gamma_0$$

$T \ll \omega_D, E_F$

electron – phonon

$\Gamma(T) \sim T^5$

electron – electron

$\Gamma(T) \sim T^2$

$\omega_D \ll T \ll E_F$

electron – phonon

$\Gamma(T) \sim T$

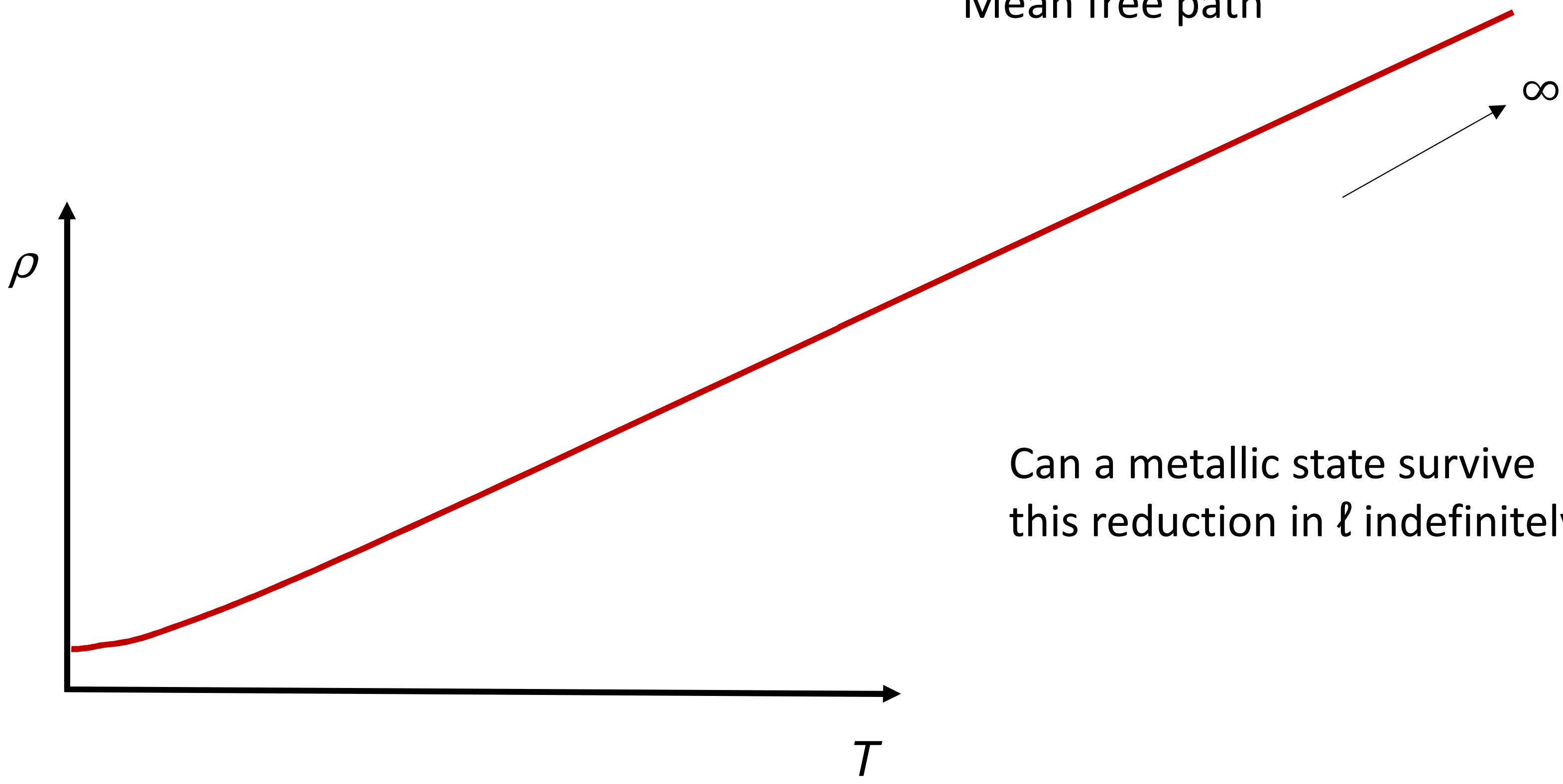
+ electron – any excitation (magnons…)

What constitutes metallic behaviour?

Basic definition: A material whose resistivity increases with temperature

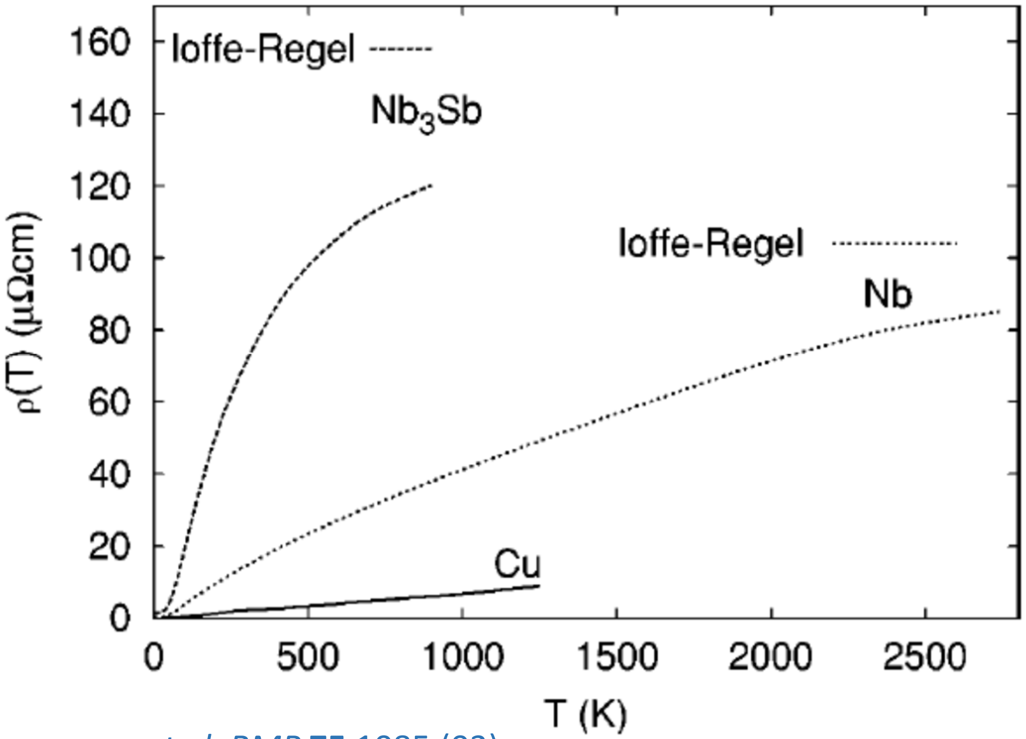
According to the Drude model: $\rho(T) = \frac{m^*}{ne^2}\Gamma(T) \propto \frac{1}{\ell(T)}$

Mean free path



Can a metallic state survive this reduction in ℓ indefinitely?

Ioffe-Mott-Regel limit



Gunnarson *et al*, *RMP* **75** 1085 (03)

$$\boxed{\rho(T) = \frac{m^*}{ne^2}\Gamma(T) \propto \frac{1}{\ell(T)}}$$

Semiclassical theory breaks down if

ℓ become shorter than the interatomic distance *a*

OR

$$\ell > \lambda_F = \frac{2\pi}{k_F}$$

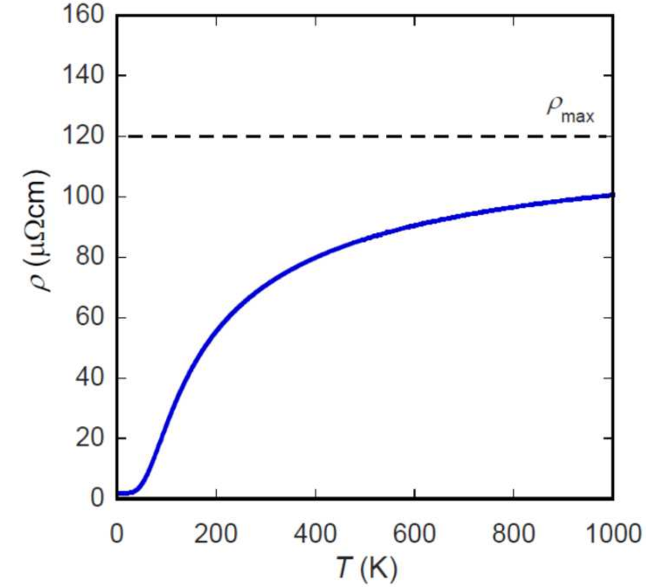
$$\boxed{k_F \ell > 1}$$

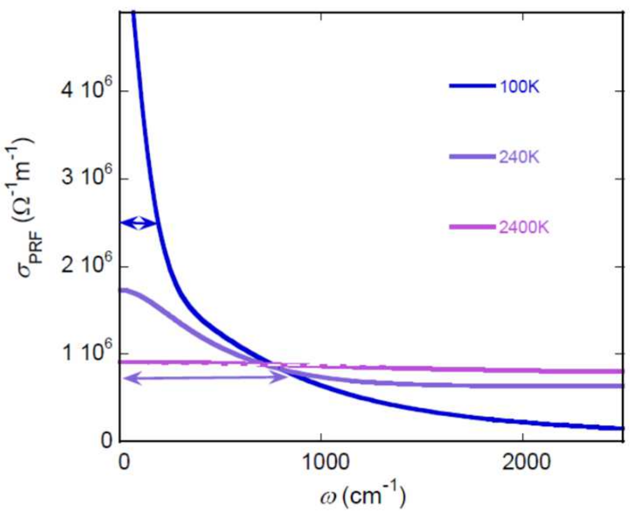
$\ell \approx a \Rightarrow$ saturation of the resistivity (Δk ~ size of Brillouin zone)

Conventional metallic transport at high T

Saturating metals

Hussey *et al*, *Phil. Mag* **84** 2847 (2004)





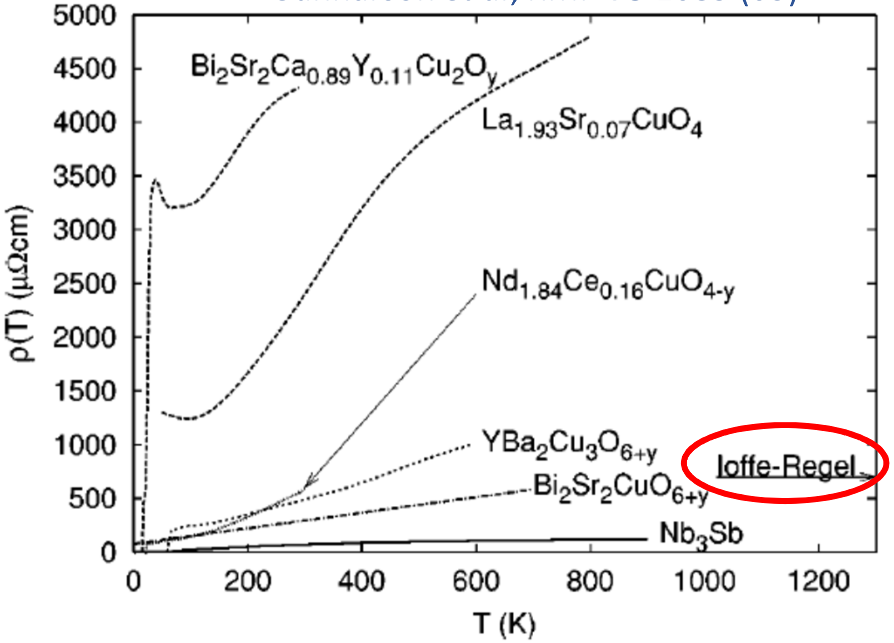
Spectral weight preserved below ω ~ W (bandwidth)

$$\sigma(\omega) = \frac{\sigma_0}{1 + \omega^2\tau^2}$$

- Drude term = coherent QP contribution
- Peak centred at $\omega = 0$ but extends up to W
- Drude peak broadens at high T with a width at half-maximum equal to $\Gamma(T < T_m)$
- Saturation of ρ ⇔ Loss of coherence of the QP
  σ(ω, T) evolves into a plateau (T < W)

Bad metallic transport in cuprates

Gunnarson *et al*, *RMP* **75** 1085 (03)

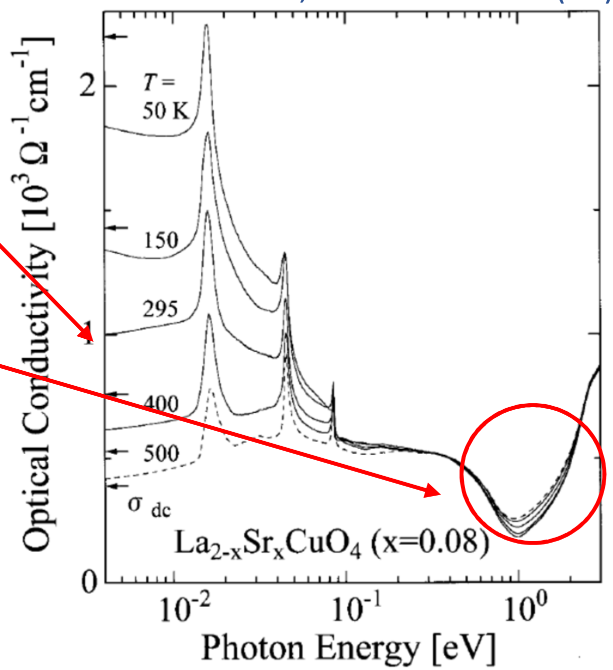


Non saturating metals:
High T_c cuprates, manganites, vanadates, ruthenates and organics

Universal feature of bad metals:

- Proximity to Mott insulator
- Strong e-e interaction

Takenaka *et al*, *PRB* **65** 092405 (02)



- Drude peak disappears around σ_0 ~ 700 – 1000 $\Omega^{-1}cm^{-1}$ (value close to the MIR limit)

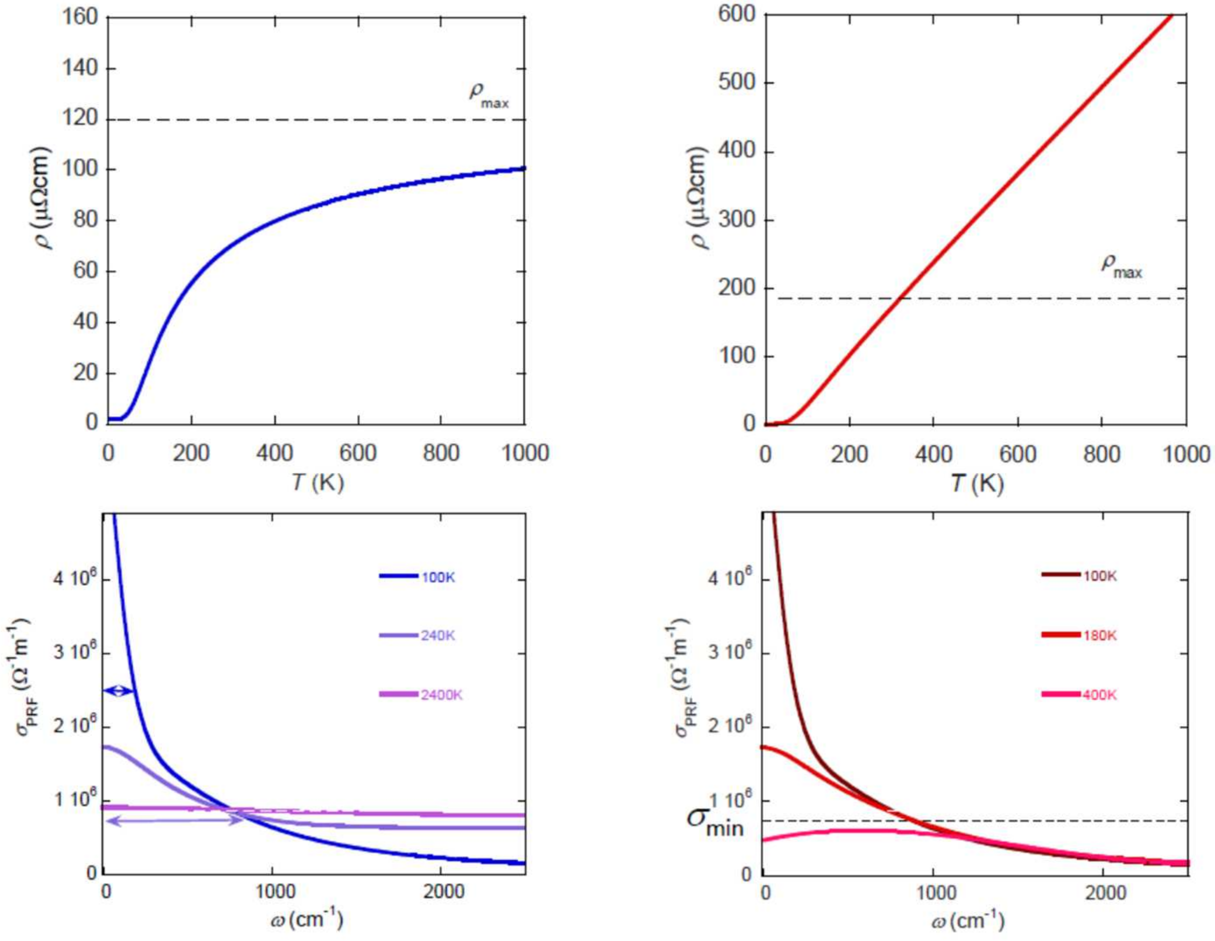
- Lost spectral weight recovered at $\omega > W$

Coherent to incoherent cross-over in the optical conductivity along with the loss of spectral weight (within W) may explain the non saturating resistivity in 'bad metals'

Conventional vs bad metallic transport at high T

Saturating metals — *Bad metals*

Hussey *et al*, *Phil. Mag* **84** 2847 (2004)



Spectral weight preserved below $\omega \sim W$

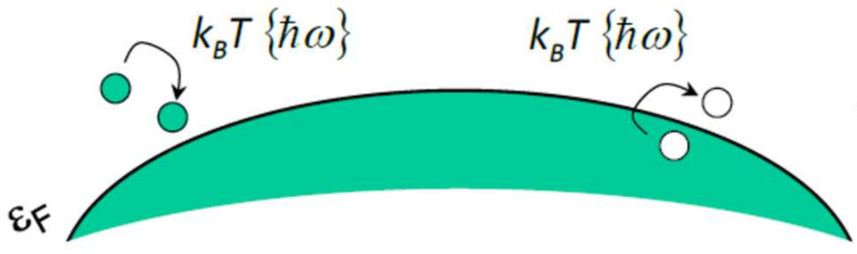
Low-freq. spectral weight displaced to $\omega > W$

- ✓ Low ω dip
- ✓ T-indept σ(ω) at high ω
- ✓ T_{crit} and $\sigma_{crit}(0)$

A bad metal behaves as if it is a QP insulator which is render metallic by collective fluctuations (e.g. CDW, SDW, stripes…)

Low temperature: T^2 resistivity

Correlated Fermi liquid at low T



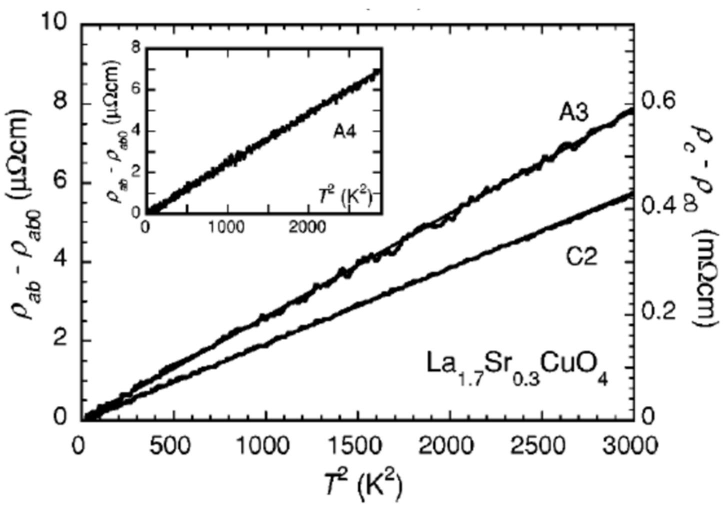
$$\frac{1}{\tau} \propto (k_B T)^2 \left\{ + \left(\frac{\hbar\omega}{2\pi} \right)^2 \right\}$$

$$\rho \propto T^2$$

T^2 resistivity originates from electron-electron scattering processes near E_F

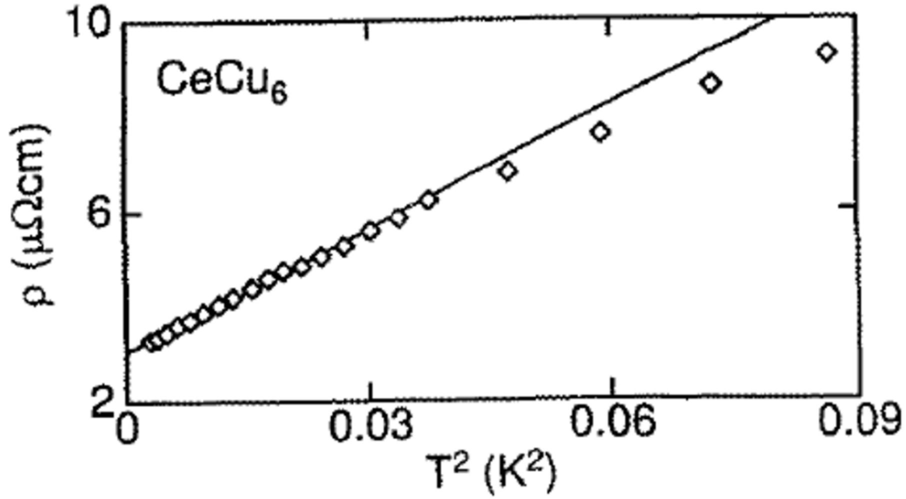
Electrons participating in the scattering event are those confined to a width of $k_B T / E_F$

Overdoped cuprates



Nakamae *et al*, *PRB* **68** 100502 (2003)

Heavy fermions

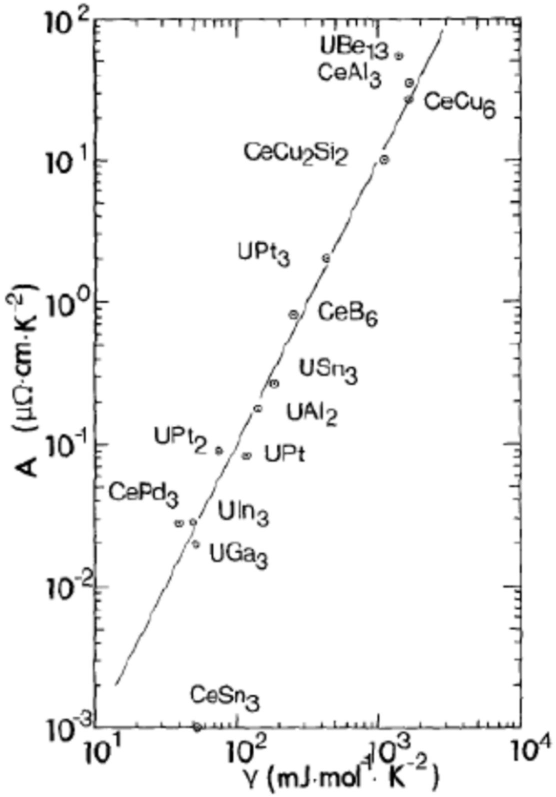


Lohneysen, *JPCM* **8** 9689 (1996)

Kadowaki-Woods ratio

$$\rho(T) = \rho_0 + AT^2$$
$$C_{el} = \gamma T = \frac{\pi^2}{6} k_B^2 N(\varepsilon_F) T$$
$$A/\gamma^2 = \text{const.} \Rightarrow A \propto N(\varepsilon_F)^2$$

Yamada & Yoshida, *Prog.Theor.Phys.* **76** 621 (86)
Auerbach & Levin, *JAP* **61** 3162 (87)
Coleman, *PRL* **59** 1026 (87)
Miyake, Matsuura & Varma, *SSC* **71** 1149 (89)
Kontani, *JPSJ* **73** 515 (04)
:
:



Kadowaki & Woods,
SSC **58** 507 (86)

$$A/\gamma^2 \sim a_0 = 10^{-5}\ \mu\Omega\text{cm.mol}^2.\text{K}^2/\text{J}^2$$

$$A \propto \gamma_0^2 \propto m^{*2}$$

$$A_i = \left(\frac{8\pi^3 ack_B^2}{e^2\hbar^3}\right)\cdot\left(\frac{m_i^{*2}}{k_{Fi}^3}\right)$$

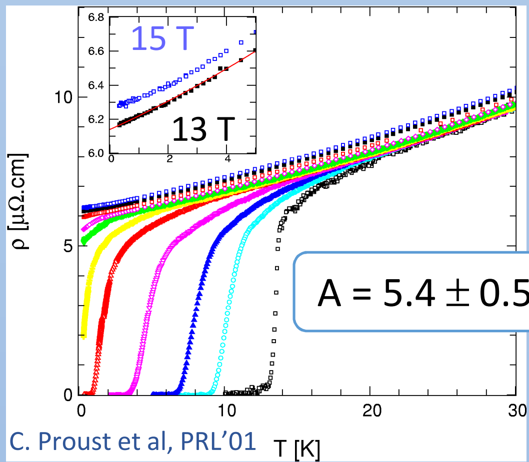
Hussey, JPSJ **74** 1107 (2005)

Correlated Fermi liquid at low T

$$\rho = \rho_0 + A\,T^2$$

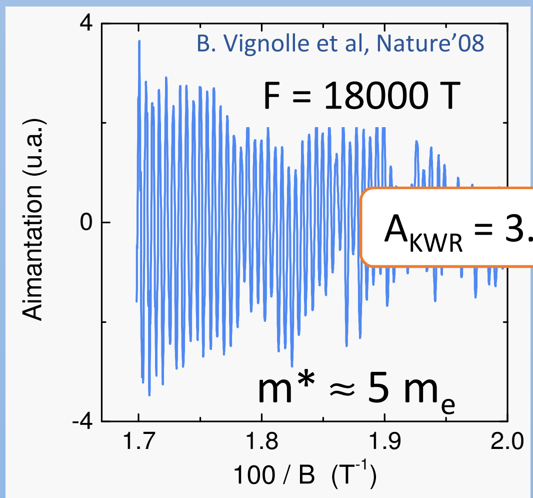
$$A_i = \left(\frac{8\pi^3 a c k_B^2}{e^2 \hbar^3}\right)\cdot\left(\frac{m_i^{*2}}{k_{Fi}^3}\right)$$

$Tl_2Ba_2CuO_{6+\delta}$



C. Proust et al, PRL'01

$A = 5.4 \pm 0.5$ nΩ cm K^{-2}



B. Vignolle et al, Nature'08

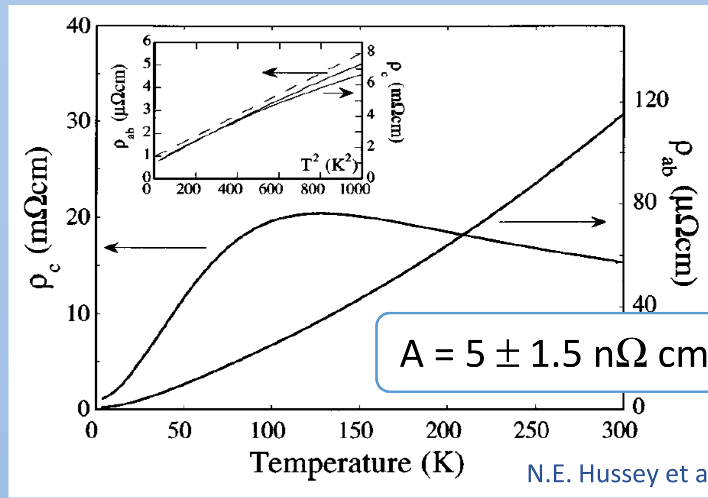
F = 18000 T

$m^* \approx 5\,m_e$

$A_{KWR} = 3.9$ nΩ cm K^{-2}

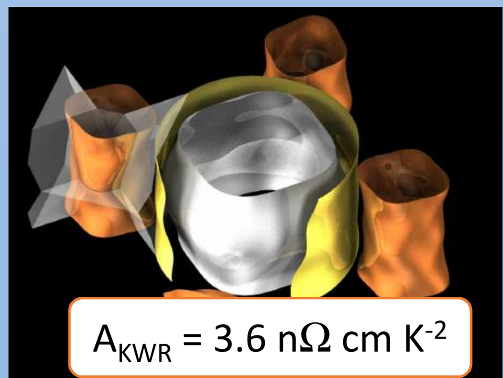
Sr_2RuO_4

Multi-band system $\Rightarrow \frac{1}{A} = \sum_i \frac{1}{A_i}$



$A = 5 \pm 1.5$ nΩ cm K^{-2}

N.E. Hussey et al, PRB'98



$A_{KWR} = 3.6$ nΩ cm K^{-2}

TABLE II. Summary of quasiparticle parameters of Sr_2RuO_4.

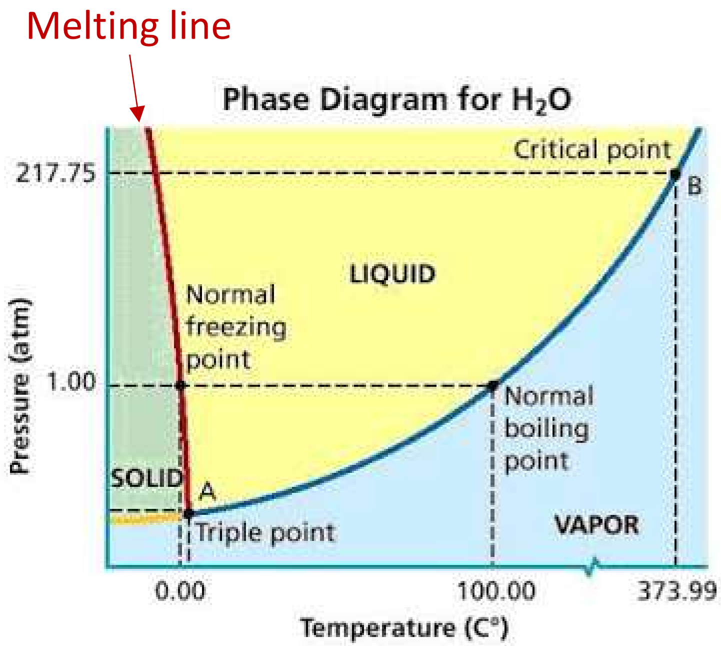
Fermi-surface sheet	α	β	γ
Character	Holelike	Electronlike	Electronlike
k_F (Å^{-1})[a]	0.304	0.622	0.753
m^* (m_e)[b]	3.3	7.0	16.0
m^*/m_{band}[c]	3.0	3.5	5.5
v_F (ms^{-1})[d]	1.0×10^5	1.0×10^5	5.5×10^4
$\langle v_\perp^2\rangle$ ($m^2 s^{-2}$)[e]	7.4×10^5	3.1×10^6	1.0×10^5
$t_\perp$ (K)[f]	7.3	15.0	2.7

C. Bergemann et al, Ad. Phys.'03

Low temperature: Quantum criticality

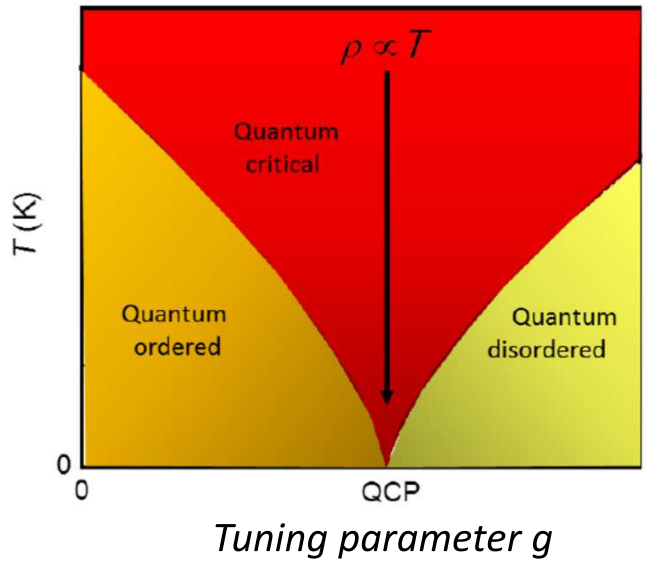
Quantum criticality

'Classical' phase transition



Melting of ice = increase in thermal motion of the molecules as *T* is raised

Quantum phase transition



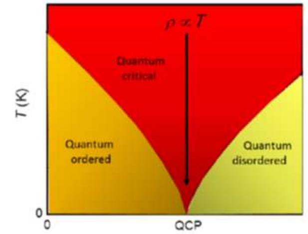
Phase transition that is driven not by T but by quantum fluctuations ('zero point motion')

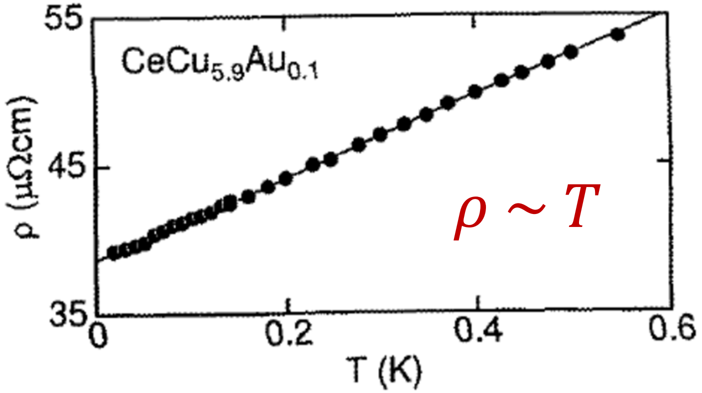
$$\Delta x . \Delta p \ \geq \ \hbar$$

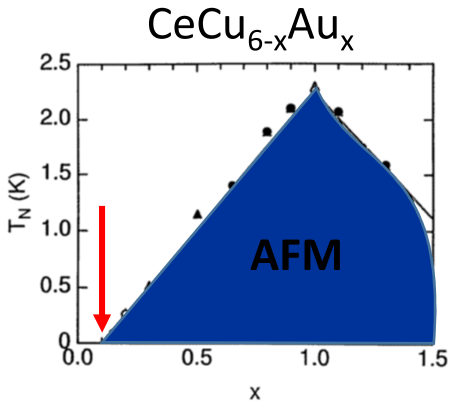
As T $\rightarrow$ 0, thermal motion ceases but electron cannot be at rest (Δx *and* Δp fixed)

$\Rightarrow$ « State of constant agitation »
that can melt order

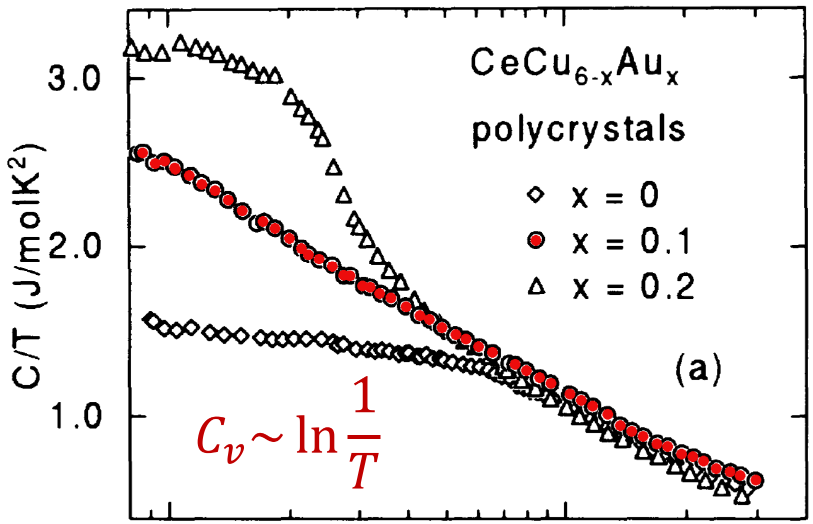
Quantum critical metals



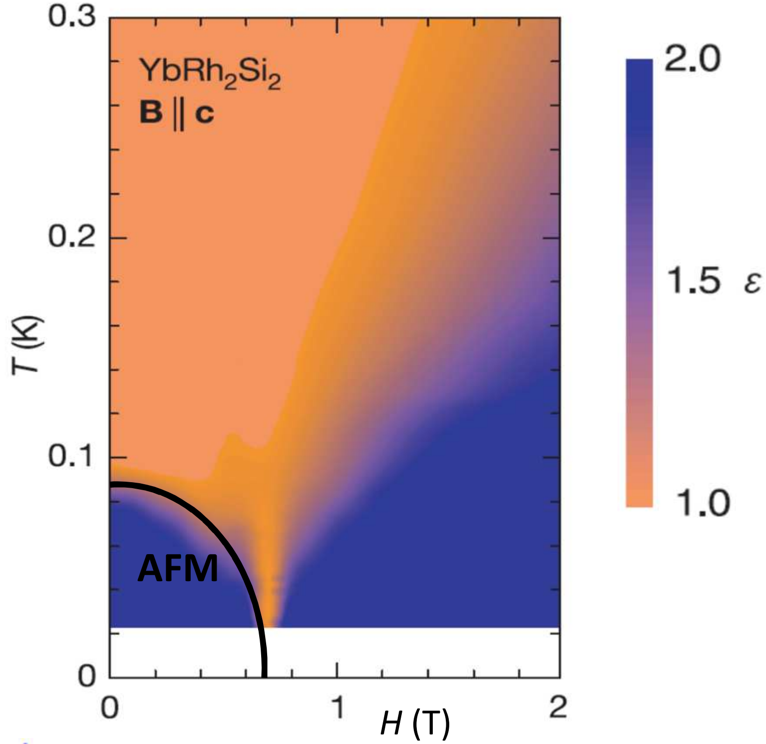




Lohneysen, *JPCM* **8** 9689 (1996)



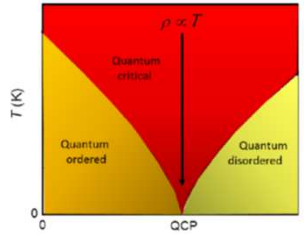
$C_v \sim m^* \Rightarrow m^* \to \infty$ at a QCP !

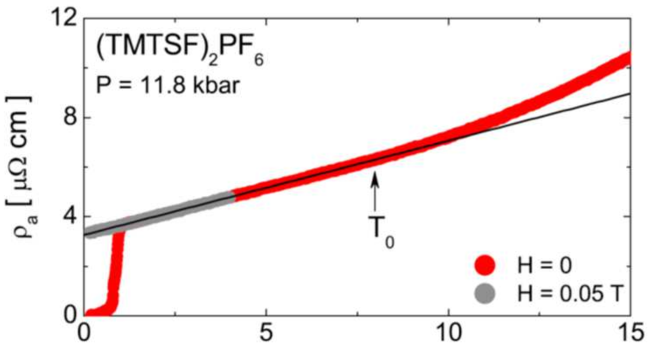


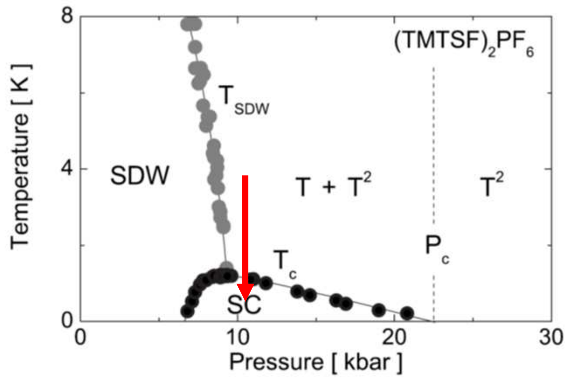
Custers *et al.*,
Nature **424** 524 (03)

$\rho = \rho_0 + A' T^{\varepsilon}$

Quantum critical metals

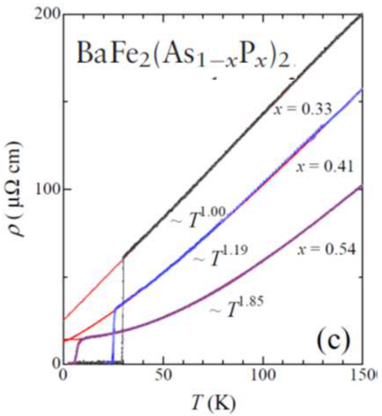


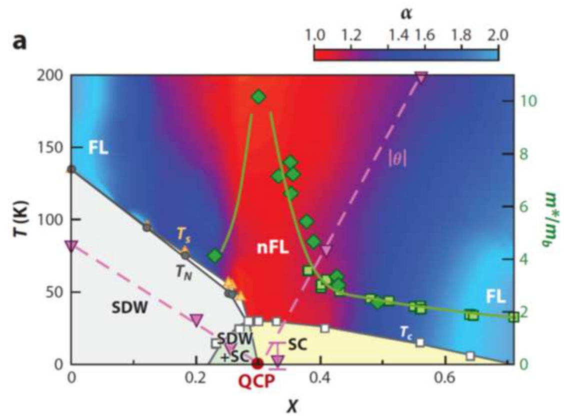




Organic superconductors

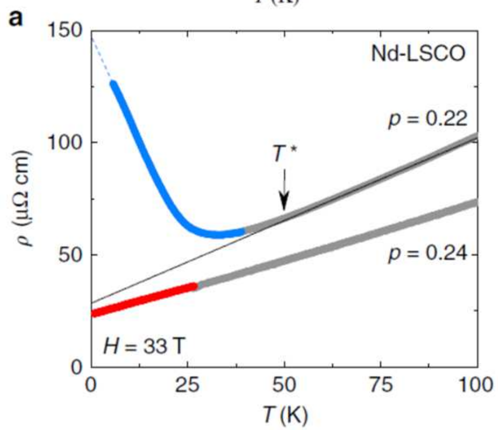
Doiron-Leyraud *et al*,
PRB **80** 214531 (2009)

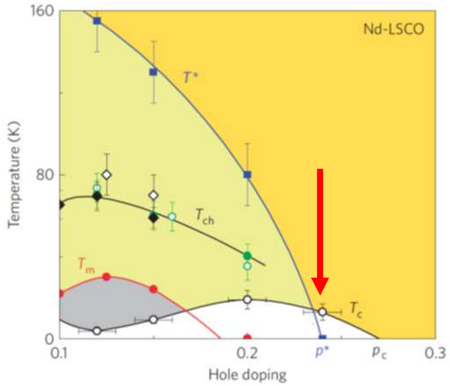




Pnictides

Shibauchi *et al*,
ARCMP **5** 1113 (2014)





Cuprates

Daou *et al*,
Nature Phys. **5** 31 (2009)

Origin of the T-linear resistivity

VOLUME 82, NUMBER 21 PHYSICAL REVIEW LETTERS 24 MAY 1999

Interplay of Disorder and Spin Fluctuations in the Resistivity near a Quantum Critical Point

A. Rosch

$\rho \sim T$

Competition of weak, but isotropic impurity scattering and strong scattering from spin-fluctuations

PHYSICAL REVIEW B VOLUME 51, NUMBER 14 1 APRIL 1995-II

Resistivity as a function of temperature for models with hot spots on the Fermi surface

R. Hlubina* and T. M. Rice

BUT

Only effective at "hot spots" on the FS connected by the AF wavevector !
The rest of the FS short-circuit the anomalous transport and yield $\rho \sim T^2$

Locally critical quantum phase transitions in strongly correlated metals

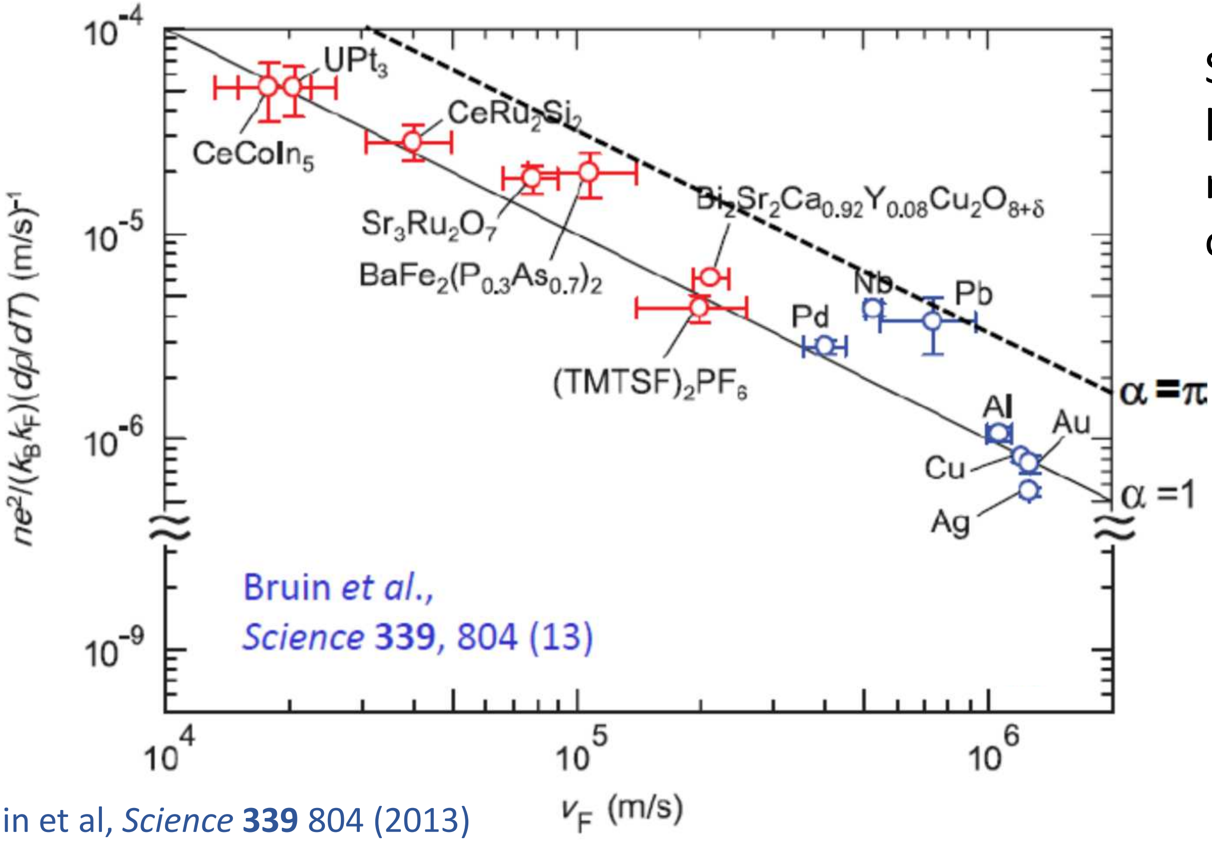
Qimiao Si*, Silvio Rabello*, Kevin Ingersent† & J. Lleweilun Smith*

Nature 413,804 (2001)

Proposition: scattering near a QCP have a local character, i.e. no k-dependence
$\Rightarrow$ the entire FS is "hot“ : Marginal Fermi liquid with $\rho \sim T$

Origin of the T-linear resistivity

Planckian dissipation



Bruin et al, *Science* **339** 804 (2013)

Similar scattering rate per kelvin of metals in which resistivity is linear in T (QCP or e-ph scattering)

$$\boxed{\hbar/\tau \sim \alpha k_B T}$$

T is the only relevant energy scale

For SCES, $0.9 < \alpha < 2.2$ in spite of differences in dimensionality and microscopic nature of the interactions.

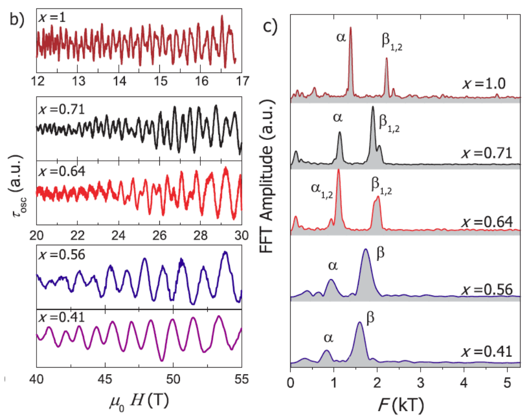
The law of quantum mechanism forbids the dissipation time to be any shorter then τ

4. High fields transport properties

Why high magnetic field ?

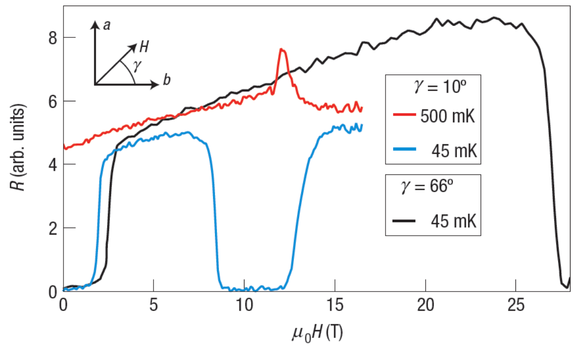
RESOLVE FERMIOLOGY

$BaFe_2(As_{1-x}P_x)_2$



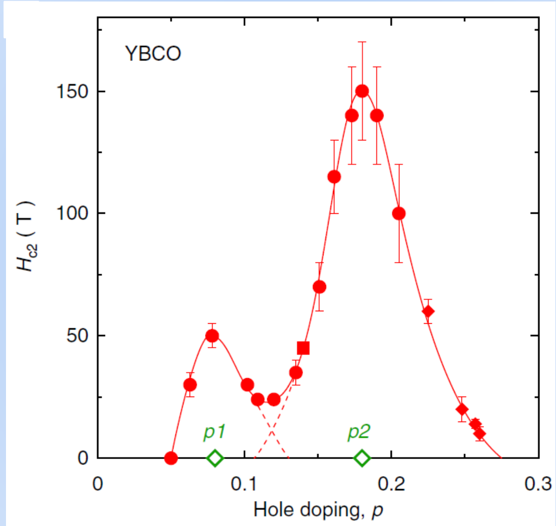
H. Shishido *et al.* PRL **104**, 057008 (2010)

INDUCE NEW STATES OF MATTER & NEW PROPERTIES



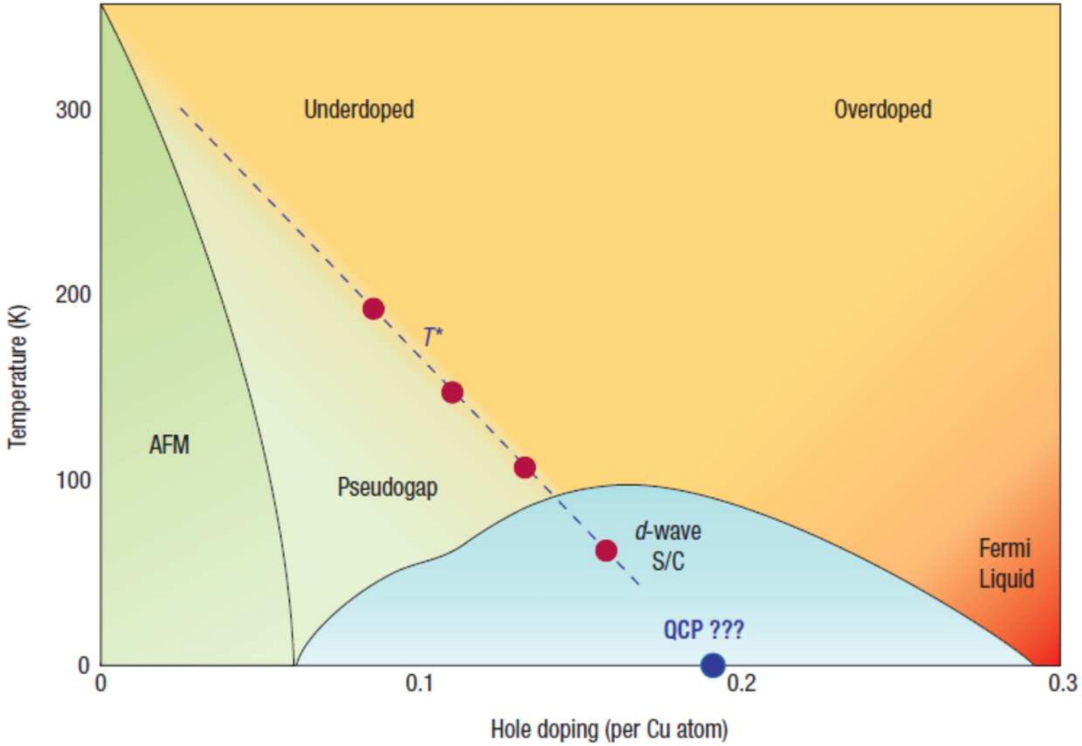
F. Lévy *et al.* Nature Phys. **3**, 460 (2007)

RESTORE THE NORMAL STATE OF SUPERCONDUCTORS



G. Grissonnanche *et al.* Nature Comm. **5**, 3280 (2014)

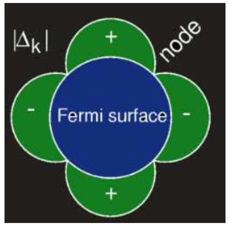
Pseudogap and quantum criticality in cuprates



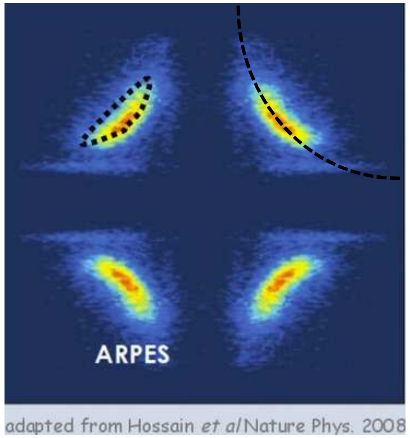
« Although it is difficult to predict the role that quantum criticality will play in our final understanding of the cuprates, the case for a QCP would be made very compelling if a new experiment were to reveal a sharp and pronounced change in some electronic property in the zero-temperature limit, on crossing the QCP as a function of doping. »

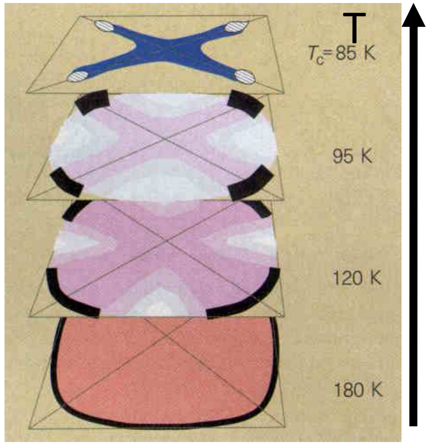
Broun, *Nature Physics* **4** 170 (2008)

Pseudogap and quantum criticality in cuprates

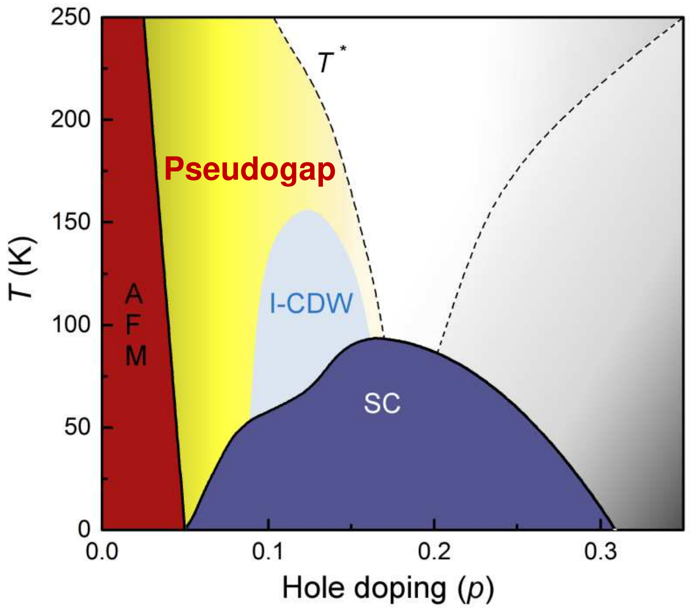


ARPES





M. Norman *et al*, Nature'98

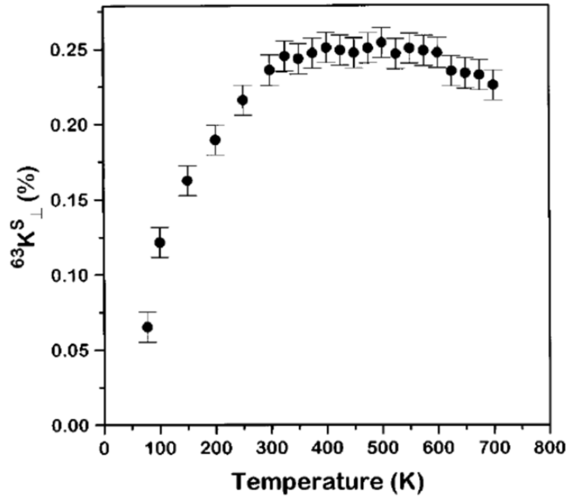


Partial suppression of the low energy excitation as seen by spectroscopy and thermodynamic probes and located at the anti-node

Doped Mott insulator ?

Phase with a distinct order parameter?

NMR: Pseudogap for T<T* (crossover)

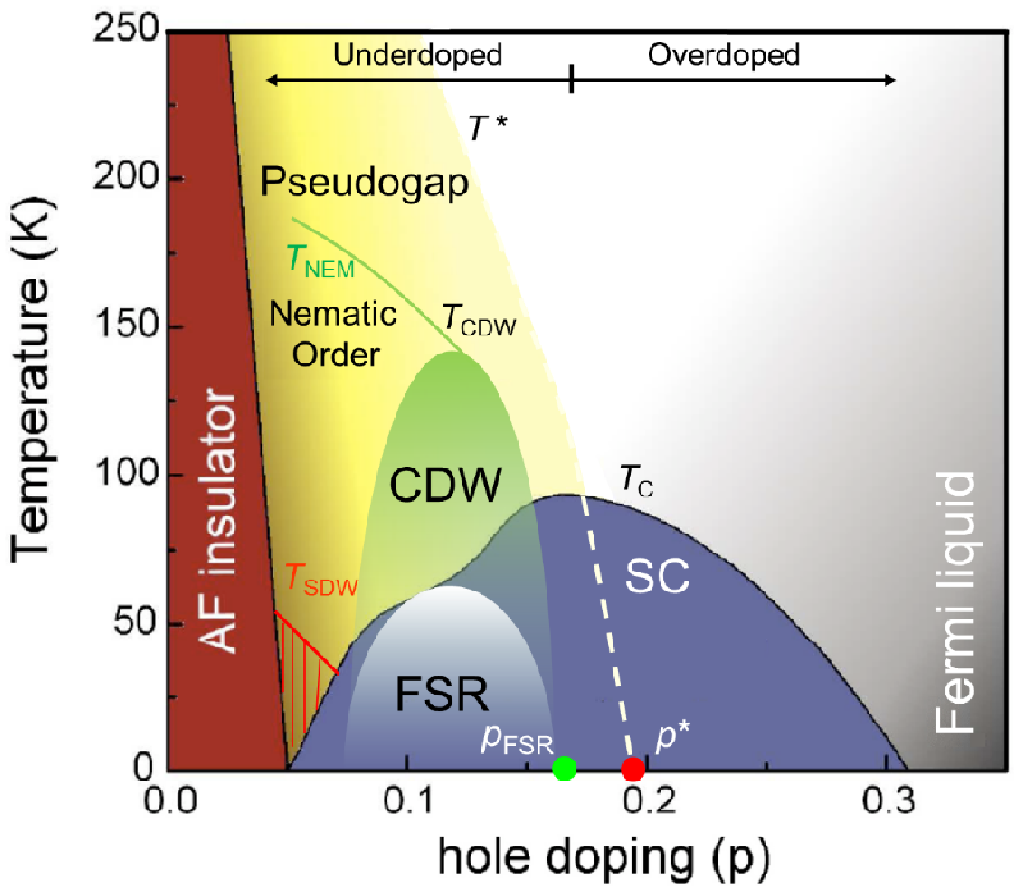


Curro et al, PRB 56, 877 (1997)

$K \propto \chi'(q=0,\omega) \propto$ DOS

Pseudogap and quantum criticality in cuprates

Pseudogap = partial suppression of the low energy excitation as seen by spectroscopy and thermodynamic probes and located at the anti-node (from ARPES)



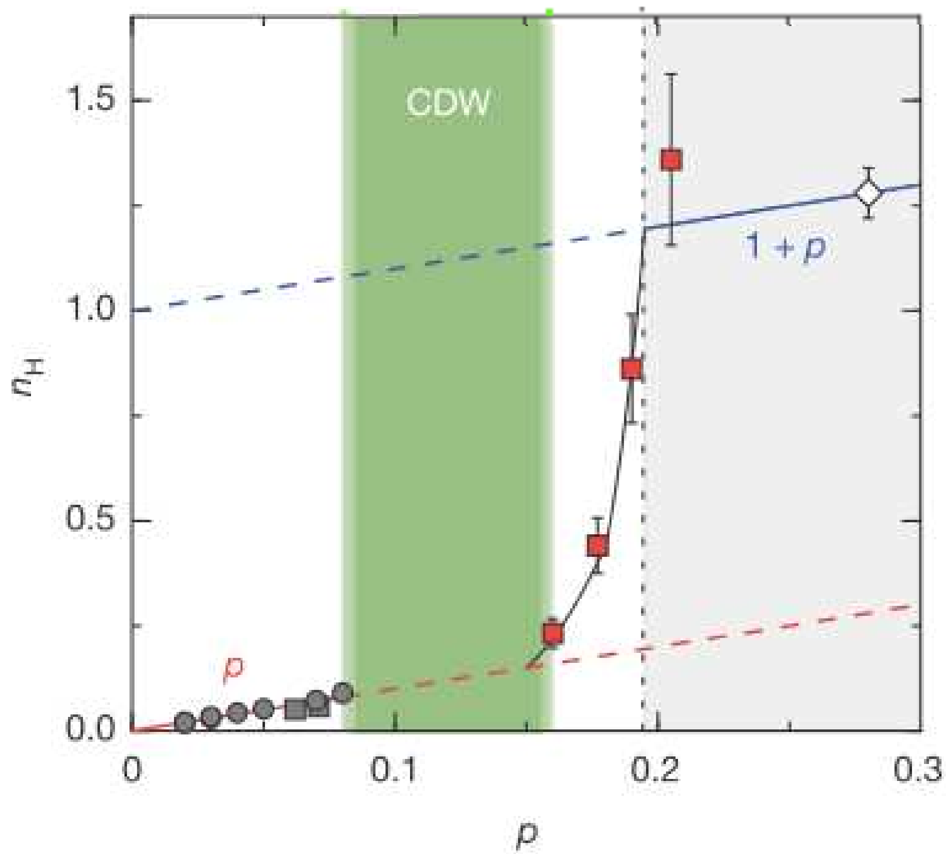
- ✓ Orbital current
- ✓ Nematic
- ✓ ~~CDW~~
- ✓ AF **?**

Q=0

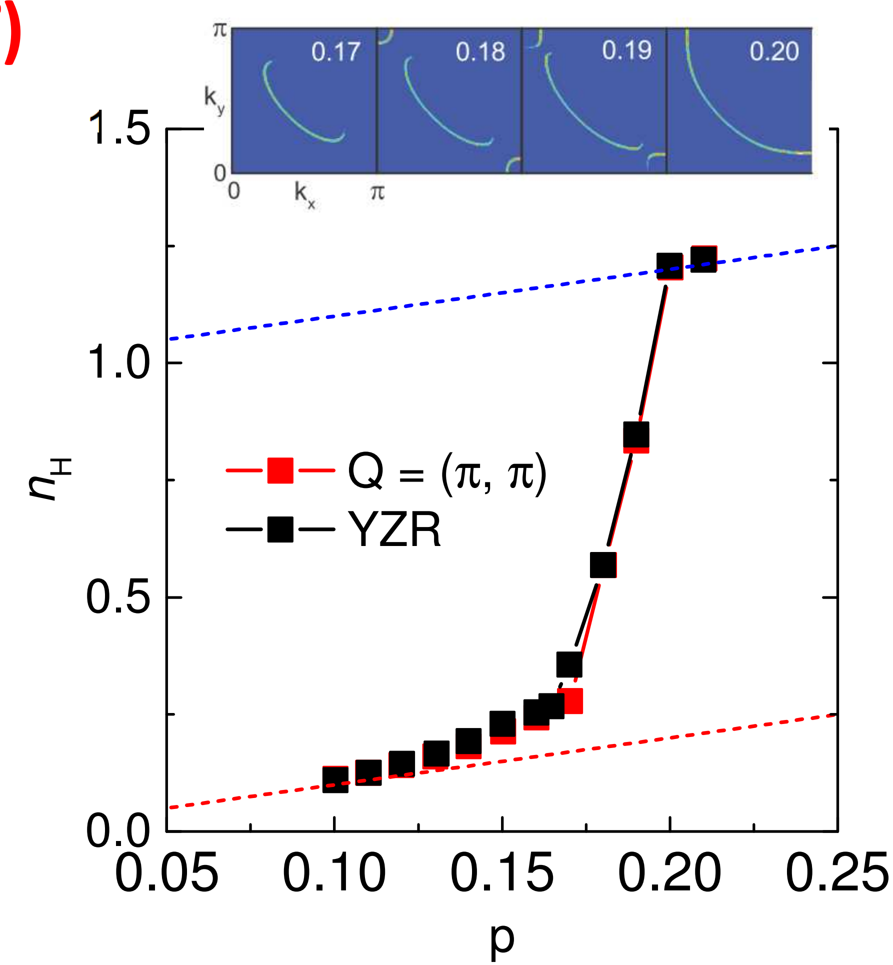
The broken symmetries are instability of the pseudogap

Pseudogap and quantum criticality in cuprates

Low T (H = 80 T)



S. Badoux *et al.*, Nature (2016)



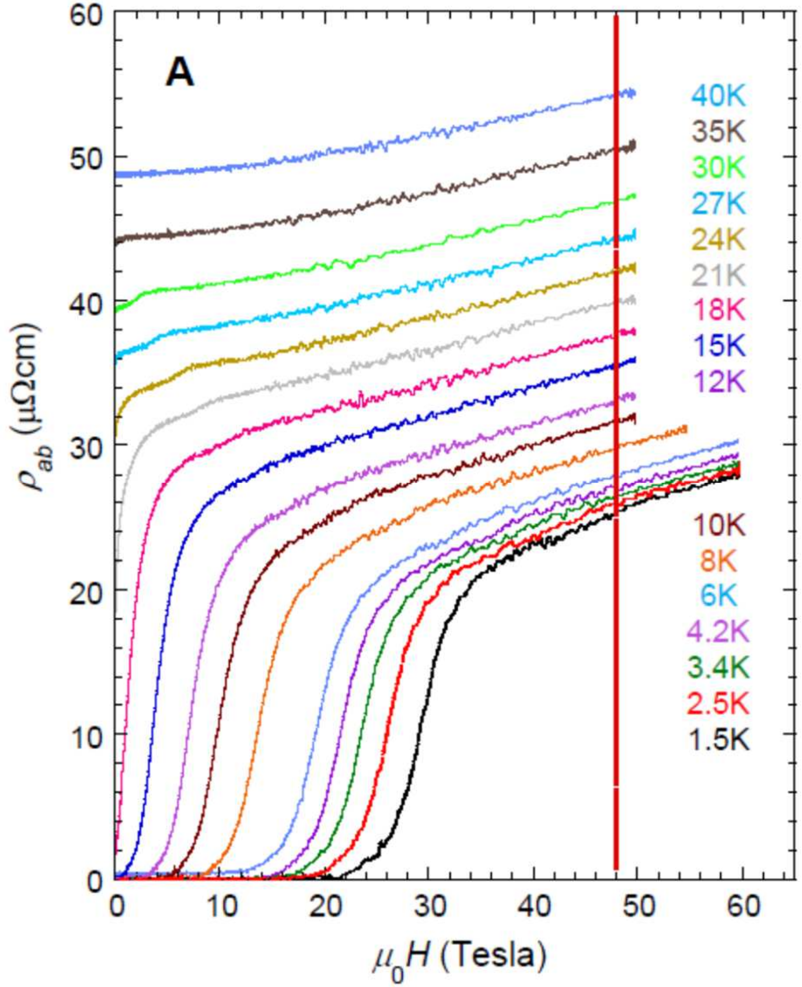
J.G. Storey *et al.*, Euro. Phys. Lett. (2016)

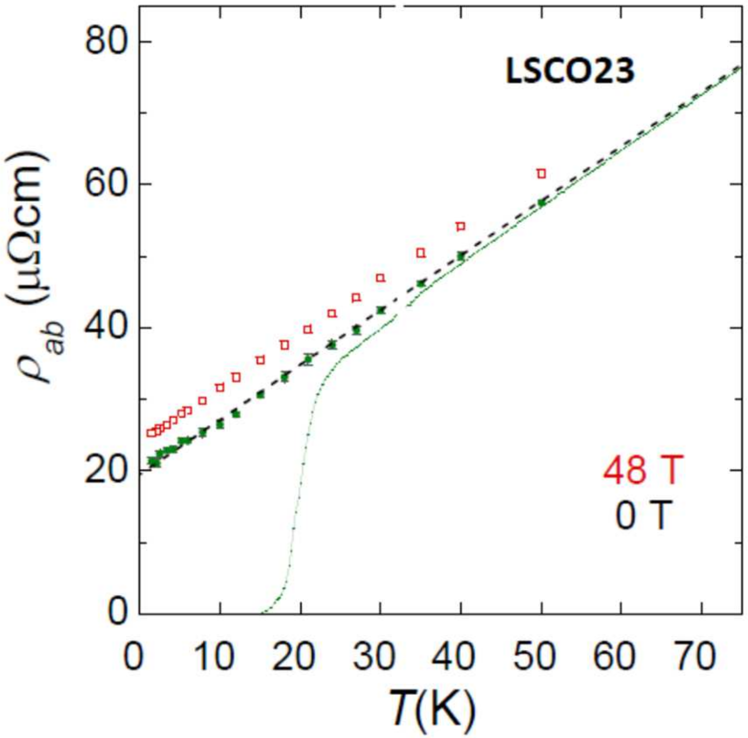
- Pseudogap and charge order are separate phenomena.
- Sharp drop of the carrier density at the critical point of the pseudogap.

High fields transport properties in LSCO

Access ground state using pulsed magnetic fields

T-linear term becomes dominant at low *T*



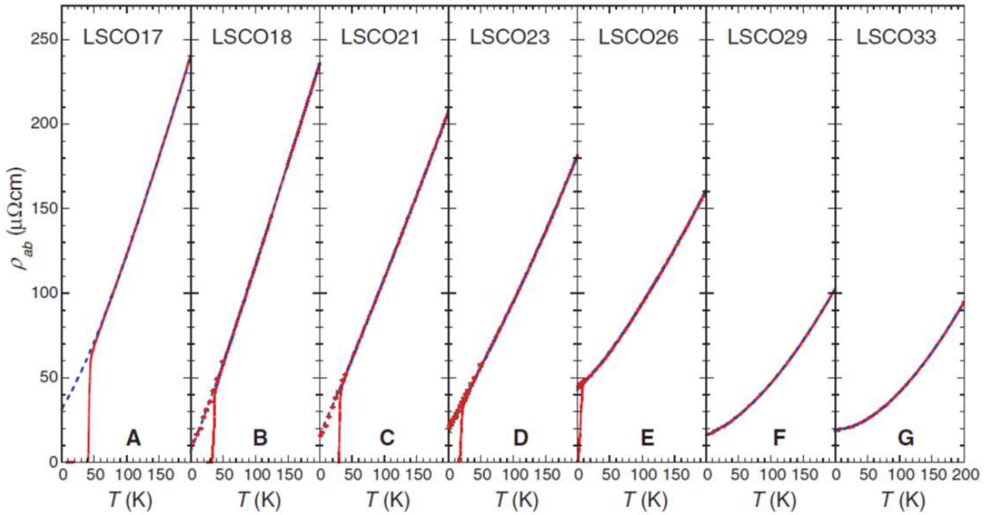


Cooper *et al.*, *Science* **323**, 603 (2009)

Anomalous criticality in LSCO

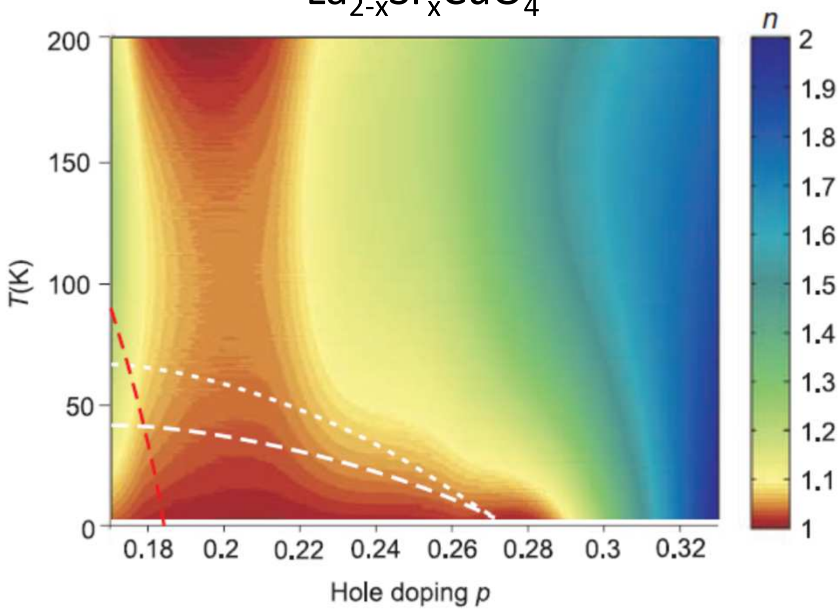
Cooper *et al.*, *Science* **323**, 603 (2009)

$\rho_{ab}(T)$ remains T-linear at low T over an anomalously wide doping range



$$\Delta\rho_{ab}(T) = \alpha_n T^n$$

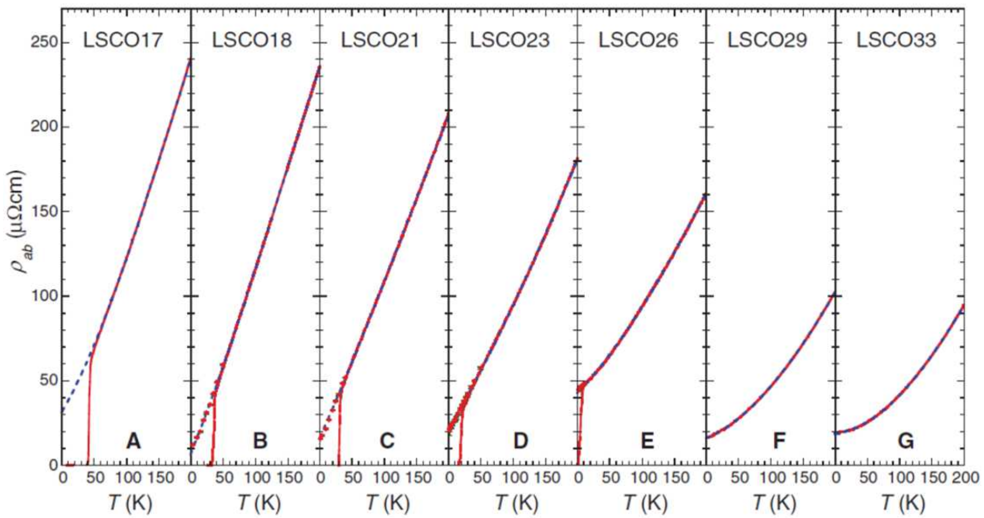
$La_{2-x}Sr_xCuO_4$



Anomalous criticality in LSCO

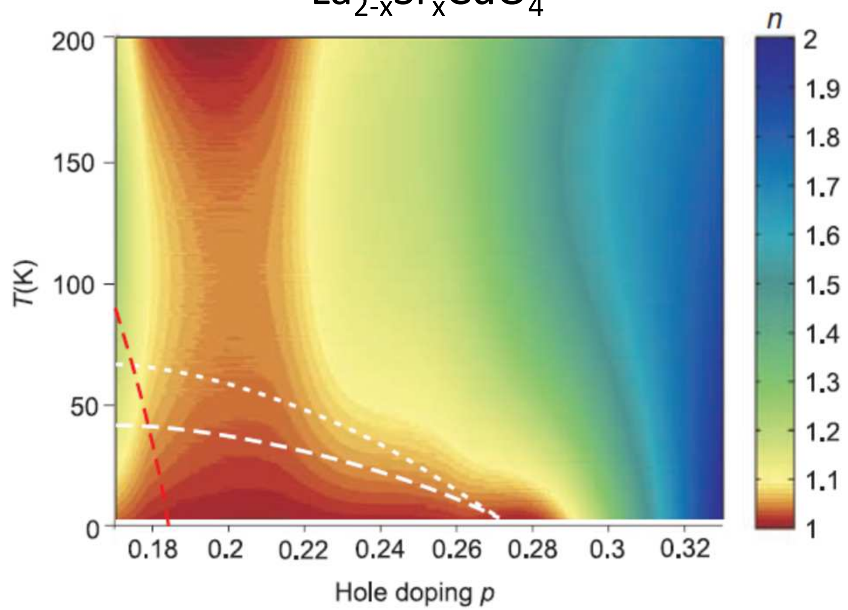
Cooper *et al.*, *Science* **323**, 603 (2009)

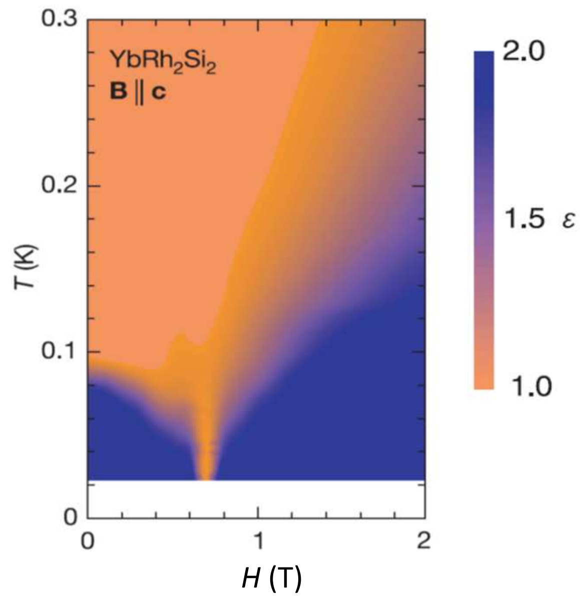
$\rho_{ab}(T)$ remains T-linear at low T over an anomalously wide doping range



$$\Delta\rho_{ab}(T) = \alpha_n T^n$$

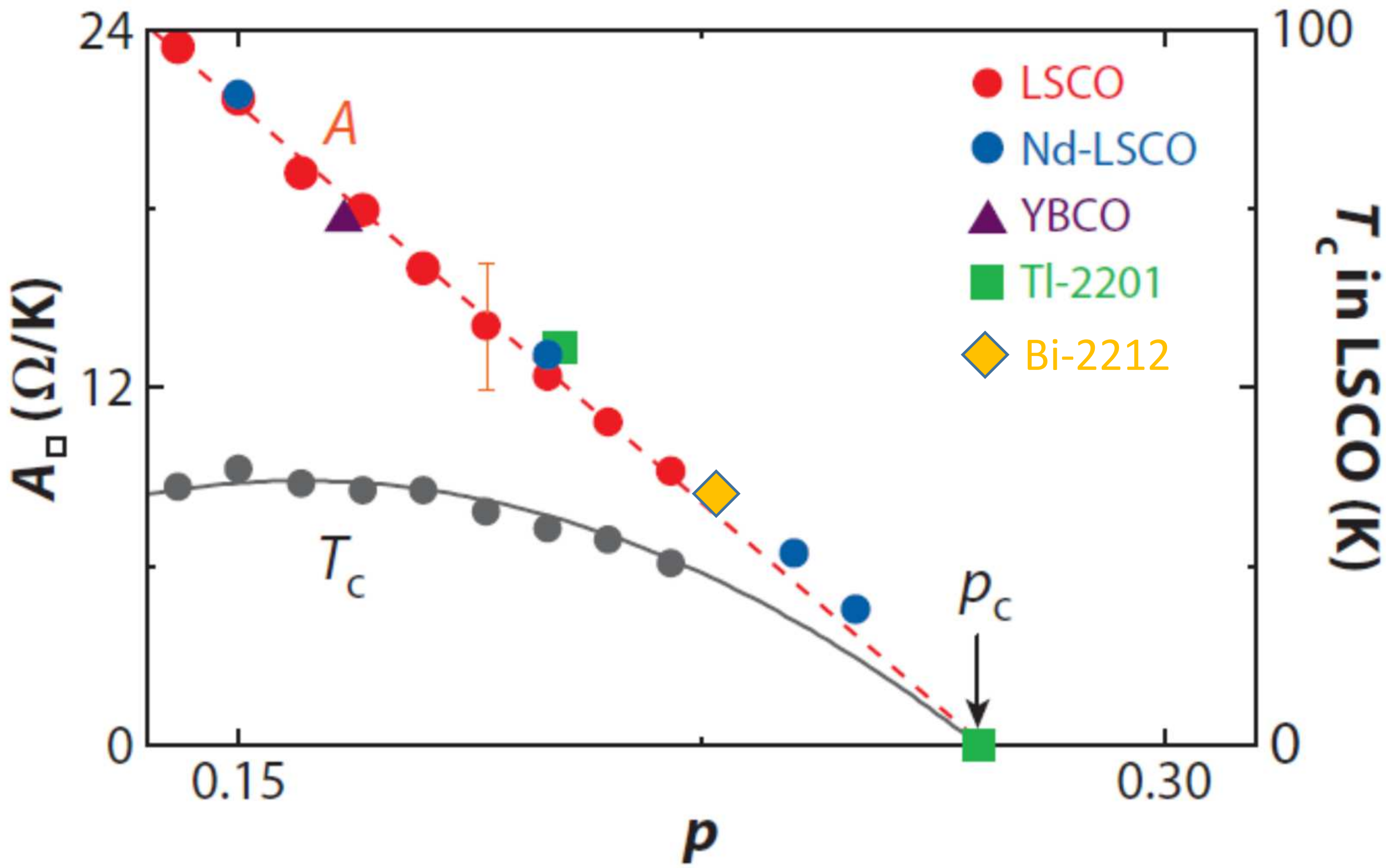
$La_{2-x}Sr_xCuO_4$





Discussion

Doping dependence of the linear term of the resistivity in hole-doped cuprates



"What scatters may also pair"

Taillefer, *ARCMP* **1**, 51 (2010)